

Final Report

Virginia Tech OSH Research Cooperative Agreement

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Document 1: Final Progress Report

Abstract

Title: Virginia Tech OSH Research Cooperative Agreement

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Over the last five years, eight research projects have been conducted, each with a unique impact on the occupational safety and health of workers in the construction industry. Here is a brief explanation of each of the projects and their results:

- 1) In order to reduce construction worker's exposure to welding fumes, researchers developed sensors that can detect the presence of nanoscale aerosols generated during the welding process with extremely high sensitivity. NORA goal 6.5 was addressed in this project.
- 2) Research was conducted with immigrant Latino workers to determine if electronic data collection, in particular, computer-assisted telephone surveys (CATS), would be a useful tool to capture and understand their daily processes and important safety behaviors. It was determined that with refinement the tools would be useful in gathering this data. The researchers addressed NORA goals, 9, 10, 12 and 7.3.3.
- 3) Another project involving Latino construction workers investigated using a lay health advisor, or a community health worker, to educate workers about fall protection and prevention. They found that there was no significant differences between safety knowledge and behavior between participants. They learned that for such programs to be effective, workers' values surrounding the need for employment and income should be addressed as they were hesitant to participate in the program fearing alienation from their employers. NORA goals 9, 10 and 12 were addressed.
- 4) A team of researchers compared safety strategies between the United States and Australia, whose safety record is twice as good as the U.S. They determined that decisions made in the design process, or pre-construction phase, on hazards, can have a major impact on safety as opposed to making the decisions during construction. This implies the need for architects, engineers and constructors to work together in pre-construction. Case studies were developed based on this research to be used as training tools. NORA goal 10 was addressed in this research.
- 5) Twenty-year work-related injuries and illnesses among union carpenters in Washington State were analyzed by evaluating worker's compensation claims compared to Bureau of Labor Statistics patterns. It was determined that injury and illness rates are actually higher than the Bureau of Labor Statistics report. Other findings suggest a shifting of care to private insurance over time, and that drywall installers are at a high risk for a variety of injuries. These methods should serve as a model for improved occupational safety surveillance. NORA goals addressed in this research are 7.2, 8.2 and 14.1.

- 6) Using a proactive prevention through design approach, researchers developed a decision support system for panelized construction to help reduce work-related musculoskeletal disorders. They addressed NORA goals 13 and 7 in this research.
- 7) Another project researched how to improve use of prevention through design tools, which greatly reduce safety and health hazards, in the construction industry, specifically a ventilated sanding tool. The findings showed that training regarding risks to the worker health, hands-on training with the tools, cues-to-action (i.e. hard hat stickers, t-shirts) reminders to work safely, and developing a 'technology champion', someone who was allowed to use new equipment for a trial period, within the contractor community were the most effective strategies. NORA goals 5.2 and 5.3 were addressed in this project.
- 8) The trends and barriers of adopting prevention through design technologies was researched in the concrete, masonry, asphalt roofing, and welding industries. After surveying the industry, it was found the following as motivators to adopting safer technology: safety, government regulations and insurance incentives. The barriers were productivity, job performance and cost. NORA goal 13 was addressed in this research.

Section I: 2-Page Final Progress Reports by Subproject

Project ID 644 - Novel Optical Systems for Real-Time Welding Fume Monitoring

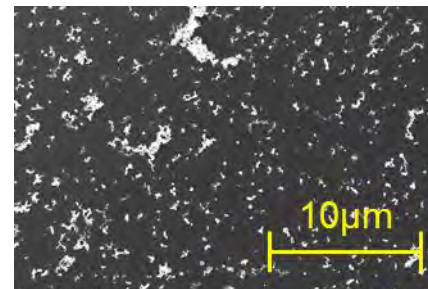
A.1. Significant (Key) Findings

The most significant finding of this project is the demonstration of an optical system capable of detecting the presence of nanoscale welding aerosols with high sensitivity. Such a sensing system directly addresses aim 2 of the project, where we propose to use the scattering of light by welding aerosols for optical sensing. To facilitate future translation into practical construction practices, in designing such a sensing system, we have taken the following factors into consideration. First of all, we require that the sensor itself must be miniature in size, readily available, easy to fabricate and calibrate, inexpensive, and capable of achieving high sensitivity. To satisfy these requirements, we choose to use silica-based fiber devices that can support high quality (Q) factor whispering gallery modes (WGMs). Theoretically, the existence of WGMs can be attributed to the simple fact that silica-based fiber devices tend to possess extremely smooth surfaces with minimal scattering. Therefore, if we use such a silica-based device as our sensor, due to the almost complete light reflection at the silica interface, optical signals can travel along the sensor surface for a long distance with minimal loss. A direct consequence is that by measuring the transmission of optical signals through such a sensor that supports high-Q WGMs, we can readily identify multiple sharp transmission dips, where each dip corresponds to a specific WGM. Using a commercial silica fiber as the sensor, we have developed a protocol that allows us to reliably identify a specific WGM for aerosol sensing. Perhaps more importantly, we find that if the sensor surface is accumulated with welding aerosols, the transmission dip associated with the aforementioned WGM would shift. After extensive experimental characterization, we have established an empirical relationship that links the WGM resonance shift with the amount of welding aerosols accumulated onto sensor surface. Then, by measuring the resonance shift in real time, we should be able to achieve WGM-based welding aerosol sensing.

After extensive experimental characterization, we find our WGM-based sensor design has three distinct advantages. First of all, it is significantly more sensitive than existing approaches that are based primarily on cascade impactors. In existing impactor design, one must first collect sufficient welding aerosols before one can use a microbalance for mass measurements. Typically, the mass of collected aerosols must exceed 1 μg . In contrast, we estimate that our WGM-based design can detect welding aerosols with total weight as low as 1-10 ng. Secondly, the WGM-based system can detect nanoscale welding aerosols. In the figure above, we show a scanning electron microscope (SEM) image of welding aerosols that can be detected using our fiber sensor. The diameters of the welding aerosols shown in the figure are mostly below 250 nm, and typically vary in the range of 50 to 100 nm. Finally, the WGM fiber sensor itself is small (125 μm in diameter and < 2 cm in length), widely available commercially, and cost very little (less than \$1). We anticipate that these unique features of our WGM-based sensor design should greatly facilitate practical translation.

Next, we have constructed a low cost spectroscopy system capable of measuring the emission spectra of light generated by the welding process, which is our aim 1. Using this system to monitor a typical welding process in real time, we find multiple peaks in the captured emission spectra and identified several peaks characteristics of elements such as Cr and Ni. For additional verification, we find that we can use the measured emission spectra to identify welding rods / work pieces that contain elements such as Cr and Ni.

Finally, we have established two different optical systems for Raman spectroscopy, which is the goal for aim 3. One of the two systems is based on free space optics, where we have demonstrated that we can detect the presence of a single micron-sized particle attached to a silica fiber taper. The other system



relies on the existence of WGM for sensitivity enhancement. The principle has been demonstrated using a silica fiber ring structure that supports WGMs.

A.2. Translation of Findings

First of all, the results obtained during our experimental study suggest that the silica-fiber-based WGM sensor can be directly used for nanoscale aerosol sensing, which is becoming increasingly important in construction practices.

Additionally, given the ultra-high sensitivity of the WGM-based aerosol sensor, it can also find applications that complement existing construction practices. For example, in current cascade-impactor-based approach, one must “artificially” pump air through the cascade impactor for aerosol collection. And in order to collect sufficient amount of aerosols for weight measurements, the total volume of air pumped through the impactor must be sufficiently large. In contrast, for our WGM-based aerosol sensor, due to its high sensitivity, such practice is no longer necessary. In fact, in our current experiments, we simply let the welding aerosols naturally drift towards the fiber sensor and become adsorbed onto sensor surface, with no “artificial” air flow at all. As such, we find a highly relevant phenomenon, which is the fact that the majority of welding aerosols attached to the fiber sensor are nanoscale in sizes, with aerosol diameter typically less than 250 nm. A likely explanation is that without “artificial” air flow, smaller aerosols (i.e., those that are nanoscale in sizes) are more likely to drift further and be captured by the fiber sensor. If, on the other hand, we were to utilize a cascade impactor for aerosol collection and analyses, we must sample a sufficiently large air volume, and may not be able to discover the dominance of nanoscale aerosols in regions further from the welding arc. In summary, our fiber-based aerosol sensor should enable researchers to map the distribution of nanoscale aerosols without any external perturbation in the form of “artificial” air flow for aerosol sampling and collection.

It is also worthwhile to point out that due to the low cost of the silica-fiber based WGM sensor, it is feasible to deploy a large number of such sensors at multiple locations within a construction site for real-time distributive sensing, i.e., measuring aerosol concentrations at multiple locations. If desired, we can also deploy the optical emission spectroscopy and the Raman spectroscopy system to provide information on aerosol composition. Due to the size and cost of these two systems, however, it may not be feasible for multipoint monitoring.

A.3. Outcomes / Impact

The optical systems developed here can generate significant potential outcomes in the following areas.

- (1) The development of nanotechnology has made it increasingly important to monitor the presence of nanoscale particles in work places and construction sites. The silica-fiber-based WGM sensor that we developed for welding aerosol monitoring is well suited to meet such demands.
- (2) The ultrahigh sensitivity of the WGM sensor is also relevant for applications that require sensitivity that exceeds the capability of existing cascade-impactor-based approaches.
- (3) By multiplexing multiple low cost WMG sensors together in a fiber optic network, we should be able to simultaneously monitor aerosol concentrations at multiple sensing locations in real time. No existing cascade-impactor-based particle sensing technology is capable of this functionality. Therefore, the adoption of our technology can open up new avenues of investigation. For example, with our WGM sensor based technology, it is now possible investigate, in real time, whether nanoscale aerosols are homogeneously or heterogeneously distributed throughout a specific construction site.
- (4) Minor modifications of sensor design may enable us to tailor these optical systems for different types of sensing applications.

Project ID 647 - Micro-Processes of Latino Construction Worker Safety: Feasibility of Computer-Assisted Telephone Surveys

Section 1: Executive Summary

Significant (Key) Findings

This project had three aims: 1) documenting Latino construction workers' participation rates, attrition levels, and adherence to a 21-day end-of-day daily diary protocol using a completely automated telephone surveys (CATS), and loss to follow-up over 3 months of immigrant workers; 2) determining the quality of data collected from a daily process study design; and 3) identifying modifiable design features to improve feasibility of daily process study designs with immigrant Latinos. Each of these is discussed in turn.

- 1) CATS technology makes diary studies with Latino samples feasible. Our published results (Grzywacz et al. 2013) indicated that over one-third (37%) of the recruited sample adhered to the 21-day protocol, a comparable percentage (38.7%) initiated but did not adhere to the protocol, and 24% never began the diary protocol. Adherence was generally not predicted by demographic, health or job-related characteristics suggesting few sources of systematic bias in adherence.
- 2) Collected data were of sufficient quality to provide a foundation for three published peer-reviewed papers, in addition to the publication documenting the feasibility of using CATS with Latino workers.
 - I. Most relevant to this aim is a manuscript that combined data from the baseline interviewer-administered survey question with data obtained via CATS. The paper describes work safety climate among Latino residential construction workers, delineates differences in work safety climate by personal and employment characteristics, and determines associations of work safety climate with specific work safety behaviors (Arcury et al. 2012). Key measures included the Perceived Safety Climate Scale, and daily reports of six individual and five collective safety practices. Work safety climate was mixed among workers, with roofers (M=19.9) having lower levels than framers (M=24.3) or general construction workers (M=24.3). Days reported for several individual (glove-related risks, not doing something known to be unsafe) and collective safety practices (attended daily safety meeting, not needing to use damaged equipment, not seeing coworker create an unsafe situation) were positively associated with work safety climate. Work safety climate predicts subsequent safety behaviors among Latino residential construction workers, with differences by trade being particularly important.
 - II. Two additional analyses focused on data obtained through other components of the project. The first analysis sought to determine the potential health threat of work organization to immigrant Latino workers in selected trades in the residential construction industry using longitudinal data from a community-based sample (N=107) (Grzywacz et al. 2012a). 28 participants reported one or more work-related injuries during the 3 month observation period, resulting in an injury incidence rate of 52.8 per 100 FTE. Two injuries involved two or more days away from work, resulting in an incidence rate of 3.8 injuries involving days away from work per 100 FTE. Injuries were elevated among roofers relative to framers and general construction workers. In terms of work organization, variety and control were lowest among roofers and highest among general construction workers, and roofers reported the greatest exposure to occupational hazards. Roofers also reported the lowest levels of supervisory influence over aspects of employment (both negative and positive), and their perceived safety climate was the poorest.
 - III. The second analysis used cross-sectional data from a community-based sample of Latino construction workers in Western North Carolina (N=119) to: describe receipt of employer provided PPE by construction workers, document sources of variation in the receipt of employer-paid PPE, and delineate associations of employer-paid PPE with workers regular use of PPE (Grzywacz et al. 2012b). The results suggest substantial deviation in residential

construction subsector from regulations requiring employers to provide workers with PPE at no cost. Analyses also suggest recent immigrants are most at risk for not receiving no-cost, employer provided PPE, and that employer-provision of no-cost PPE may promote more regular use by Latino construction workers.

- 3) Results obtained from this exploratory/developmental project provided concrete recommendations for refining future implementations of CATS technology with immigrant Latino workers. A key area of refinement discovered was the quality of the computerized “voice”: it was reported by participants to sound artificial and as though it had an echo. We learned this could be addressed by using special features of the program (specifically UTF-8 Unicode as opposed to US ANSI standard character encoding) to better exploit characters, such as the Spanish accents and the tilde, to produce more authentic sounds. We also learned other programming options to help the system differentiate participants’ voices from ambient background noise over the telephone. These refinements have been incorporated into our current project using CATS technology to evaluate a Lay Health Advisor safety training program among Latino roofers.

Translation of Findings

The key finding of this exploratory/developmental project, that CATS technology makes daily process study designs feasible with immigrant Latino workers, does not have direct application to the workplace. However, it provides a powerful tool for future research on occupational safety and health.

Study results reported in the empirical papers have direct implications for preventing workplace injuries. Findings from our paper focused on the work safety climate (Arcury et al., 2012) suggest that active steps to improve the safety climate within small-scale residential construction operations will improve safety behaviors among Latino workers. Specific tactics for improving safety climate will likely differ across construction trades, but all will need to incorporate culturally-competent safety training (to equip workers to engage in safe work practices), greater enforcement of existing regulations and perhaps tax incentives (to incentivize employers to more strongly engage in safety training), and the creation of training modules and other communication strategies (e.g., social norms marketing) targeting supervisors/crew leaders highlighting the importance of subtle behaviors and attitudes pertaining to safety in fostering employees’ safe work practices.

Results from our paper focused on personal protective equipment (PPE) (Grzywacz et al., 2012b) suggest improvements in employers’ adherence to provide no-cost basic PPE would result in greater use of PPE. Advocated strategies to improve employers’ adherence were: 1) greater enforcement of existing statutes, which would be made possible through the creation of a contractor registration system that used common criterion across all states, and 2) the creation of tax credits for the provision of PPE to employees to incentive small-scale contractors who frequently have thin profit margins to provide PPE.

Outcomes/Impact

The results of this exploratory/development project do not have any intermediate or end outcomes for worker safety and health. However, the results have substantial potential to improve worker safety and health. The potential lies primarily in the ability of future research using CATS technology to: 1) identify new risk factors for occupational health, and 2) evaluate interventions to change workers’ safety behavior. These, in turn, will likely create new best practices for promoting safety and health among immigrant Latino workers employed in the small-scale residential construction industry.

Project ID 648 - From Finger-Pointing to Lifesaving: A Supply Chain Approach to Construction OSH

SECTION 1. SUMMARY: SIGNIFICANT FINDINGS, TRANSLATION, OUTCOMES

In benchmarking (e.g. Kleiner, 1994), the objective is to identify best practices that can be adopted or adapted. For this project, we identify infrastructure, and other contextual factors that likely contribute to the US:AU disparity in safety performance. Using a matched case study approach, we investigate US versus AU projects relative to delivery system (i.e. design/bid/build, design/build, accelerated, collaborative) and sector (i.e. residential, commercial, industrial, heavy) in terms of roles and safety decision making. We also report on whether roles in the supply chain lead to differences in risk perception/hazard identification. Finally and most significantly, we have designed and developed several useful and usable r2p products.

The specific aims of this project were to:

1. Map, analyze, and model the sociotechnical roles, relationships, information flows, interactions, and interdependencies that occur during the lifecycle of construction projects and impact OSH outcomes during the construction stage. The analysis will include the collection of data from projects representative of different sectors of the construction industry (e.g., residential, commercial, and industrial and heavy engineering), as well as projects procured by different delivery mechanisms (e.g., design-bid-build, design and construct, accelerated, and project alliancing).
2. Measure and graphically map the similarity/difference between the OSH attitudes and occupants' understandings of different sociotechnical roles in the construction industry. The understanding generated by the analysis will identify the underlying mechanisms by which occupants of disparate professional and functional roles form judgments of OSH risk and make decisions and take actions based on these judgments.
3. Evaluate the impact of collaborative project delivery methods and procurement strategies on OSH performance through the development of shared mental models of OSH and the creation of a unity of purpose with regard to project/industry OSH outcomes.

Significant Findings

The average Hierarchy of Control score at case level was statistically different between the US and AU. AU had a significantly higher HOC score than US. This result suggests that the higher levels of the Hierarchy of Controls, which are more design-oriented, is attended to more, as compared to the US.

The percentage of hazards in a project that were addressed during pre-construction were statistically different between US and AU. AU addresses safety challenges in the pre-construction phase at a significantly different level than the US. Simply, hazard identification occurs earlier in the process in Australia than in the US and differences in safety performance result.

The results showed a positive, significant correlation when decisions on the response to a hazard are performed more often in the pre-construction stage for both data sets. Similar to the previous finding, this result validates the effectiveness when safety decisions are made upstream at the pre-construction stage. Additionally, the results showed a significant difference on Hierarchy of Control intervention when an activity is controlled during the pre-construction versus construction stage of a project.

The constructor or key subcontractor being involved in the pre-construction stage has a positive effect on safety (HOC). Regarding roles and the prescription to make safety decisions earlier, contractor and subcontractor involvement upstream positively affects performance. On a related note, the results indicated a positive effect of supplier engagement early in the procurement process as a strategy to improve social sustainability outcomes.

There is no absolute within-group homogeneity among professional groups nor are between-group differences always evident with respect to participants' OSH risk perceptions associated with the selected building systems/technologies. Simply, designers, constructors and others do not differ in their risk perceptions. This could actually be beneficial in upstream safety collaboration and decision making. For example, downstream constructors do not have a heightened sensitivity for safety that would need to be imparted upon designers for effective collaborations.

Translation of Findings

Aim 3 was focused on translating r2p deliverables. Several deliverables are attached to this report. Collectively, they translate the following into practice:

- AU is more advanced in implementing higher-level controls than US.
- At least addressing the hazard earlier can lead to more high-level controls.
- Decisions made during the design stage of a project can have a significant “downstream” impact upon OSH.
- The integration of process knowledge into product design decisions can significantly improve the quality of OSH risk control in construction
- Consideration of OSH early (in pre-construction stages of the project life-cycle) can be linked to implementing higher order controls for OSH risks during the construction stage
- OSH risk is subjective in nature and individual risk perception is the result of the interplay between these attributes

In addition, case studies were developed as part of Aim 1. These case studies have been shown to be quite useful as training tools.

Outcomes and Impact

This project involved an unprecedented international benchmarking framework with a subcontractor in a country whose construction safety record, as measured by fatalities per 100,000, is twice as good as the U.S. record. The project itself was an exemplar for collaboration in general, and international collaboration, in particular. The project generated extremely valuable r2p products, and more than 15 publications. It is also believed that this project broke new ground on the feasibility and effectiveness of international collaboration for improvements in the US Construction Industry. The project team overcame many obstacles at the outset. Today, benchmarking other countries who outperform the US in OSH is much more accepted.

Project ID 652 – A Decision Support System (DSS) for Ergonomic Construction Design

SIGNIFICANT (KEY) FINDINGS

This project involved three separate components, with an overall objective of finalizing and applying a Decision Support System (DSS) to enhance both ergonomics and productivity in panelized residential construction. The first component addressed the assessment of ergonomics in panelized construction, especially musculoskeletal aspects. A new biomechanical model was developed to assess low-back loading, and assessments of this model indicated that satisfactory performance was possible for a wide range of manual handling tasks relevant to panelized construction. In addition, extensive lab-based task recreations were completed (some aspects of which were conducted in an earlier funded project), and used to assess important influences of task-related factors on low back injury risks. Injury risks were found to be high overall, quite high in some cases, and with important main and interactive influences of task factors including panel weight, origin height, and the number of available workers. Only a subset of the vast number of possible combinations of task factors could be tested in the lab, yet there is a need in the DSS to generate ergonomic assessment. To address this, preliminary work was completed on methods to make more generalized task-based predictions, via interpolation/extrapolation, from compiled experimental data. The success of such predictions appeared to be substantially task dependent, as well as depending on the specific assessment measure/metric employed. This latter work is ongoing.

The second component involved substantial refinements to an earlier prototype DSS. Fundamental lean concepts and principles were applied through new algorithms to address the first two of these problems. Results from computational experiments indicated that this approach results in improved performance, has general applicability, and outperforms several existing methods. The discrete-event panelized residential construction simulator, an integral component of the noted prototype and current DSS, was substantially refined and expanded. For this, existing approaches were not appropriate, and thus a new approach was developed based upon elements of earlier methods. This new approach was needed for system-level simulation of panelized residential construction, as this is a complex, multi-worker physical process. Subsequently, algorithms were developed and incorporated into the DSS based again on lean concepts and principles. Preliminary results from a field study are presented (additional work is ongoing), involving a pair of houses (one constructed the “traditional” way and one guided by the DSS). These results show that the approach can simultaneously improve productivity, construction workload, and worker injury risks.

In the third component, methods for file-based ergonomic exposure and risk assessment were developed and assessed. A wearable system for tracking worker postures and motions during manual handling tasks was assessed in a lab setting, with results indicating the conditions under which such systems can perform favorably or otherwise. A second study developed methods to integrate this wearable system with another system that tracks in-shoe pressure; results indicated favorable performance of some methods, and which can facilitate more comprehensive ergonomic assessments in future field research. Two additional studies assessed methods for analyzing the extensive data obtained from such wearable systems, and indicated which approaches are more effective. Several novel algorithms have been developed to address these three problems; our approach stems from several fundamental principles, many of which are based on concepts derived from lean manufacturing.

A variety of algorithmic and heuristic software applications were developed and implemented, as were fundamental and applied contributions regarding the application of lean methods in construction, modeling of complex physical processing systems involving humans, the task-dependency of

ergonomics risks, ergonomics assessments, and field data collection/processing. Preliminary results indicate the broad and substantial potential benefits possible using the DSS.

TRANSLATION OF FINDINGS

Our results support several specific recommendations and general guidance to prevent workplace injury in panelized residential construction (and beyond).

- There are inherent barriers to the use of prevention-through-design (PtD) to reduce ergonomic exposure in residential construction. PtD tools (software) must accommodate or address current design, manufacturing, and construction practices, limitations, and constraints.
- There are complex effects of major panel design parameters and worksite aspects on physical exposures and injury risks, often with potentially opposing influences on ergonomic and productivity aspects. This emphasizes the need, in such complex work situations, for a system that can collectively consider physical demands and productivity and that allows users to assess the tradeoffs involved.
- Addressing production and ergonomics jointly in panelized residential construction via optimization methods is computationally infeasible. Instead, heuristic methods coupled with discrete-event simulation provides a suitable approach for this problem. However, new simulation methods are needed for this complex system.
- Integration of traditional lean engineering concepts and principles can feasibly and effectively be implemented in jointly enhancing production and ergonomics.
- Methods developed in this work indicate such joint consideration is feasible and practical through the use of simulation and lean methods, and that substantial improvements are possible.
- Both predicting ergonomic risks and processing of extensive field ergonomic measures are challenging problems, for which new methods and approaches are still required; preliminary results, however, has provided some guidance on potentially useful methods.

OUTCOMES / IMPACT

Findings from the present work offer several areas of guidance for future investigations and research, both to continue a process to improve panelized wall construction and more generally to achieve PtD in this sector and others.

- The core of our approach –system-level simulation of complex tasks comprising a job together with task-based ergonomics assessments and heuristics to facilitate decision making – should be considered a viable approach for other jobs and/or sectors. Such an approach should be applicable wherever there is (or could be) a central design effort, and has the potential for substantial “downstream” positive effects.
- Our work has identified several gaps in the area of ergonomic risk assessment. Specifically, future work is needed to improve the ability to predict ergonomic risks, to support predictions over a wider range of tasks (i.e., to minimize the need for extensive data collection). Future work is also needed to provide both conceptual and practical approaches to: 1) compiling ergonomic assessments either across different types of exposures and body regions, or across multiple workers; 2) including time-dependent effects of exposures (e.g., related to task sequencing or fatigue); and 3) processing extensive ergonomic data obtained from wearable systems.
- Subsequent investigations should assess the use of such decision support tools: 1) for training and education; 2) to identify safety (in addition to ergonomic) concerns; 3) as a method to specify worker accommodations.
- Use of new discrete-event simulation methods, as well as lean concepts and principles, may provide powerful new PtD tools and approaches.

Project ID 655 - Twenty-year trends in work-related injury and illness among union carpenters

SECTION 1. SUMMARY: SIGNIFICANT FINDINGS, TRANSLATION, OUTCOMES

We conducted a series of analyses focused on understanding the occupational health and safety experiences of a large cohort of union carpenters in the State of Washington during the twenty-year period, 1989-2008. The analyses included evaluating trends in reported work-related workers' compensation (WC) claims and making comparisons to patterns seen for construction workers in reports from the Bureau of Labor Statistics (BLS), as well as examination of potential care-shifting for treatment of musculoskeletal injuries and disorders (MSDs) through the comparison of WC injury rates and private health care utilization. We conducted detailed analyses evaluating patterns of falls from height and their associated costs with attention to patterns surrounding the fall arrest standard promulgated in Washington State in 1991. Specific analyses focused on the health and safety experiences of carpenters involved in drywall installation who are at high risk of MSDs and falls from height.

Significant Findings

Through the establishment and maintenance of a well-defined occupational cohort of union carpenters, their work hours, and their reported WC experiences that could be linked on an individual basis, we were able to identify injury rates that have been, historically, considerably higher than those reported through the BLS. Marked declines in reported WC claim rates over the 20-year period were observed among members of the cohort, but they were not the same for all groups of workers or all injuries. Greater declines were seen among carpenters with less union tenure and for claims resulting in paid lost time. More substantive declines were seen for paid lost time (PLT) injuries than for injuries overall. Struck by injuries and falls from height (FFH) declined much more markedly than overexertion type injuries. BLS rates also declined but not as markedly; while absolute differences in the carpenter cohort rates and those reported through BLS declined, the relative measures have remained fairly constant.

The rates of FFH, a leading cause of morbidity and mortality in the construction industry, decreased 82% over the 20-year period. Reductions were more modest, and without demonstrable change, since 1996 when adjusting for temporal trend. Younger workers had higher rates of reported falls from height while older workers lost more days following falls. Rates of days lost decreased over time, but there was not a consistent decline in mean lost days per fall. This would indicate that falls that occur remain as serious as they have been. Cost analyses support this as well. The patterns are consistent with decreased FFH surrounding the fall standard during which time the rate of falls declined more than other types of injuries. Crude fall rates have continued to decline, but the decline in more recent years is not as substantial as that seen for other types of injuries. Explanations could include more global efforts designed to control risk as well as changes in reporting practices over time.

Drywall installation is very fast-paced, strenuous work. It is not surprising that these workers are a high risk group, for a variety of injuries including FFH, among members of this cohort. Despite this, they too experienced marked declines in injury rates between 1989 and 2008. Field experts highlighted changes that they believed improved work place safety and, in some cases, production. Drywall materials were a substantive cause of injury in nearly 20% of the WC claims of these carpenters with a third of those resulting in paid lost time from work. Drywall carpenters had back injury rates 1.63 (95% CI: 1.48-1.78) times higher than other carpenters. Rates declined over time but were accompanied by a corresponding increase in private health care utilization. Private utilization also increased with increasing years in the union and with increasing numbers of work-related overexertion back injuries.

Work-related reports of musculoskeletal disorders and injuries involving the upper extremity (UE) and the knee were common among members of the cohort as well, and they accounted for a disproportionate share of paid lost time claims. Claims involving the UE occurred at rates three times higher than those involving the knee. Drywall installers were a particularly high risk group of extremity claims, as they were for back injuries. Declining injury rates were most pronounced for MSDIs of the knee with PLT. As WC rates declined, private health care utilization increased. The increase was muted somewhat but still sustained when adjusting for other patterns of health care utilization. These findings, and the ones related to back injuries among drywall installers, suggest the decline in WC claim rates for MSDIs do not solely represent improved occupational safety in this population of construction workers, but rather also a considerable shifting of care to their private insurance over time. This may have been exacerbated by the economic recession and the accompanying collapse of the building industry. In any event, it appears likely that the declining injury rates observed in WC records do not reflect the full picture of injury experiences of these carpenters.

Survey data with over 1000 active union carpenters document feelings that it is often best not to report less severe injuries to your employer and pressures to utilize their private insurance coverage for work-related events. Further, carpenters who reported poor safety justice on their jobsites (measured through a validated scale) were particularly likely to fear reporting work injuries and were more likely not to report.

Translation of Findings

The findings from this project have led to development of a NIOSH RO1 grant application focused on very high risk drywall installers and practical implications of prevention recommendations [Schoenfisch and Nussbaum; in review 2015].

The focus of this entire project was trying to understand and improve occupational safety and health surveillance. We believe the methods we have developed to assess the potential for care-shifting are important. This is an area that is quite difficult to study in a definitive manner over any significant period of time.

Outcomes and Impact

The project has resulted in 10 peer-reviewed manuscripts, three international presentations, and one U.S. presentation. A master's project for a Duke medical student getting a joint MD/MPH and a doctoral dissertation in epidemiology resulted from the effort. While no clear direct impact can be identified, this is not surprising or unexpected, given the nature of the surveillance work. We do believe that our methods and findings add considerably to the literature that has been developing concurrently on challenges to surveillance and potential remedies. Our ability to construct and maintain this unique occupational cohort has allowed robust analyses of a number of different issues that would not have otherwise been possible. Our ability to adjust for temporal trend through the use of internal control conditions was quite important in these analyses. Many occupational safety questions cannot feasibly be addressed through experimental designs; this body of work demonstrates clearly the importance of robust longitudinal data and a cohort approach to analyses. The methods should serve as a model for improved occupational safety surveillance. It is abundantly clear that the use of data from multiple sources is preferable to solely relying on statistics from government surveillance – or from any other single source. Further, considerable information and insight can be gained from going directly to workers to inquire about their health and safety experiences, reporting practices, and the factors that influence their decisions about reporting or not and whether and where they seek medical care. Even periodic active surveillance activities, such as the survey reported here, can add important detail that allows a better understanding of the highly dynamic nature of work-related injury and illness experiences.

Project ID 658 - Dust-control Usage: Strategic Technology Intervention (DUSTI)

Section 1: Final Progress Report

Key Findings

Theory-based intervention strategies were found to be effective in improving worker and contractor willingness to use ventilated tools. The most impactful intervention methods included: training regarding risks to worker health, hands-on training with ventilated tools, cues-to-action reminders to work safely, and the development of ‘technology champions’ within the contractor community. The technology champions were created by allowing contracting firm owners to use the ventilated tool, free of charge, for a month. Once they had the experience of using the tool in daily work operations, the majority became enthusiastic champions of the tools and expressed willingness to change their work methods and to communicate about the tool to their peers in the construction industry.

Workers who went through the intervention expressed enhanced self-efficacy, trust in the ventilated tool, and willingness to use the tool in future work operations. Contractors who participated in the intervention demonstrated improved understanding of the risk of construction dust to workers, perceived ease of use and usefulness of the ventilated tool, and increased willingness to use the ventilated tool in future work operations. One of the most important aspects of the intervention strategies was the opportunity to experientially learn about the tool: to use it in actual work operations. The interventions for the workers and small contracting firm owners allowed for actual use of the tool. These interventions saw the greatest impact on participant opinions. The large contracting firms participated in web-based learning only. Even though they watched videos of the tool being used in work operations and a video of a contractor discussing the benefits of the tool, these participants did not experience major changes in opinion regarding their willingness to use the tool.

Survey instruments were developed and tested to ensure that they reliably and accurately measure the theoretical constructs of interest. A theory-based conceptual framework was developed, based on a body of previous research in health promotion and technology innovation diffusion. Time and motion analysis demonstrated that ventilated sanding tools significantly improve work through-put and productivity, along with reducing the health risks to workers.

Web-based methods of information dissemination were not found to be as effective as in-person and hands-on approaches. More work is needed to improve this mode of intervention.

Translation of Findings

The findings of this work can be directly applied to improve construction safety and health. To improve worker and contractor willingness to use safety equipment, training interventions can be developed based on the findings of these studies, in the following ways. Training should emphasize the health risks associated with the work. Workers should be provided with hands-on training, until they become comfortable with the use of the new equipment. Contractors, if allowed to use the new equipment for a trial period in their actual work operations, are far more likely to become champions of the equipment, acquire it for their own use, and promote its use to others in their trade. Cues to action – visible reminders to use the new equipment – are also effective methods of improving worksite compliance

regarding the use of new safety equipment. And, lastly, web-based training alone is not as effective as training which allows for experiential learning.

The findings of this work can also inform future research investigations in several ways. The Prevention through Design Adoption Readiness Model (PtDARM) can be used in future studies of intervention design, innovation diffusion, and health and safety behavior change. The validated survey instruments can be employed as data collection tools by researchers engaged in health and safety behavior research. And, the intervention strategies found to be effective in the current work can be applied to other PtD innovations, other construction trade sectors, and other occupational health and safety hazards.

Outcomes/Impact

1. Potential Outcomes

The findings of this work could improve construction safety and health in construction practice in the following ways:

- Development of worker training guidelines
- Improved worker training
- Improved adoption of PtD innovations among workers and contractors

2. Intermediate Outcomes

The findings of this work have the potential to improve construction safety and health management:

- Safety management programs should incorporate the findings of this work
- The American Wall and Ceiling Industry has published these findings in their trade publication
- The trade journal, Professional Safety, has accepted an article for publication, thus disseminating this work to safety professionals
- Future research is currently underway to develop similar interventions for concrete, masonry, welding, and asphalt roofing trade sectors
- Technology champions are critically important to improve PtD dissemination

3. End Outcomes

The DUSTI project has begun to see some notable impacts:

- The Occupational Safety and Health Administration (OSHA) cited this work in its recent advisory document regarding the control of silica in construction operations.
- Environment Canada has cited this work in a draft regulation regarding quartz exposures.
- The PI was invited to speak at Purdue University's annual event, "The Engineer of 2020" on PtD in engineering design.

Project ID 10183 - Prevenir Cadas: An LHA-Based Approach to Safety Education among Latino Roofers

Section 1. Summary

Significant (Key) Findings

This project had three aims: (1) developing and implementing a linguistically and culturally-appropriate LHA-based safety education curriculum targeting fall prevention for immigrant Latino construction workers employed in roofing; (2) documenting the preliminary effectiveness in using an LHA-based safety lesson to improve fall protection and prevention safety practices among Latino roofers; and (3) identifying refinements for the LHA-based safety education program to enable definitive effectiveness testing for promoting safety among Latino roofers and reducing poor occupational health outcomes.

Aim 1: Developing and implementing a linguistically and culturally-appropriate LHA-based safety education curriculum targeting fall prevention for immigrant Latino construction workers employed in roofing.

The formative assessment provided information needed the development of the intervention content. Participants' valued productivity over safety, and this had a negative influence on their safety behavior and reduced their PPE use. They understood that roofing was hazardous. They limited use of PPE when they felt it reduced productivity and when it was uncomfortable. Work environment characteristics that affected safety included company size, the physical demands of the job, lack of training, the need for work, general life stress, and distractions at work. An injury had to result in lost work time to be considered significant. Access to health care is limited by employers not providing Workers' compensation. Future research is needed to substantiate these descriptive results and to delineate factors that are associated with safety behavior and use of PPE. Interventions, based on a lay health educator model, are needed to improve safety in this population.

The development of the intervention produced a lay health advisor safety education program that included a lesson plan, flipchart, and additional existing materials, was developed in English and Spanish. In addition, the Computer-Assisted Telephone Surveys (CATS) software was improved to allow data to be maintained when interviews were interrupted and re-started.

Aim 2: Documenting the preliminary effectiveness in using an LHA-based safety lesson to improve fall protection and prevention safety practices among Latino roofers.

89 participants were recruited to the study and completed the baseline interviews, but only 78 completed the first week daily logs using CATS technology (72 who actually worked that week). The mean work safety climate score was 26.5 (SD=5.6). In the baseline interview, participants reported that the majority of employers provided PPE and that they used it most or all of the time; daily log data indicated that PPE was used for half or fewer of hours worked. 39.9% reported any injury in the last 12 months. Work safety climate was significantly correlated with the provision and use of most types of PPE, and was inversely associated with injury. Supervisors promoting safety may increase the PPE use and decrease injuries.

Intervention effectiveness: A comparison of intervention and control participants found: (1) no significant between-group differences in safety knowledge, and (2) no significant between-group

differences in safety behavior. These null results were found at both T₁ and T₂. Some safety knowledge items and safety behaviors reported were quite high, so there was little room for improvement. However, no change was found even when individual items with low baseline scores were reviewed.

Aim 3: Identifying refinements for the LHA-based safety education program to enable definitive effectiveness testing for promoting safety among Latino roofers and reducing poor occupational health outcomes.

Recruitment to the intervention study was difficult. Latino construction workers were leery about participating in the project because they did not want to alienate their employers. Evaluation data collection was burdensome for the participants. The amount of data collection (baseline interview, and three weeks of daily interviews) created too great a burden to the participants to want to initiate or continue participation. The Computer-Assisted Telephone Surveys (CATS) Technology used for the evaluation data collection was off-putting to the Latino construction workers. They did not like calling and providing data. The cost of using their cell phones was prohibitive; the project modified its protocol to provide some compensation for the use of cell phones. Finally, the dose of a single education session was too limited to have an effect. As a result, only 89 of the 120 proposed participants were recruited to the project, and only 67 of 100 proposed participants completed the intervention.

Translation of Findings

The key finding of this research speaks to the importance of work organization for the development of programs that educate workers and employers about occupation safety. The work organization and work safety culture for Latino construction workers limit the effectiveness of occupational safety training. For this study, workers were afraid to participate in the safety training or evaluation because they did not want to alienate their employers. Workers needed the income from their jobs and did not want to make changes that would alienate their employers. Workers indicated that they valued production and income over safety; they did not want to alienate their co-workers by slowing the crew for safety. Workers indicated that they used PPE when they perceived it to be important to their employers, even when they did not believe it made them safer. Efforts should address improving the work organization and increasing work safety culture to support of safety and PPE use. This will provide the context for providing safety training for workers.

Outcomes/Impact

This project does not have intermediate or end outcomes for worker safety and health. The results do have potential to improve worker safety and health by informing work safety training and intervention programs. First, such safety training and intervention programs must address worker values surrounding the need for employment and income which drives them to ignore safety standards that they feel limit their income. Second, safety training and intervention programs need to address worker trust. For small companies, workers are often related to their supervisors or employers; this limits their willingness to be involved in training and intervention programs. Workers' need for employment limits their willingness to participate in any research or program that may alienate employers. Third, the evaluations of safety training and interventions need to collect valid and reliable data, but also need to do so in a manner that is not too burdensome. Finally, safety training and intervention programs need to have a sufficient dose to have an effect.

Project ID 10302 – Prevention through Design (PtD) Adoption Readiness

Section 1: Final Progress Report

Key Findings

Results. Based on the percentage of participants reporting their firm usage rate as either “always” or “regularly”, the most commonly used methods of dust control in the concrete and masonry trades were wet methods (81.2%), ventilated tools (58.2%), sweeping compound (30.3%), and isolation systems (12.6%). Respondents reported a high perception of risk to worker health from the concrete and masonry dust (73.6% ‘strongly agree’ or ‘somewhat agree’). Governmental regulations and insurance incentives were listed as the most pressing drivers for deciding to use dust control technology. Disruption to productivity and job performance were listed as the main barriers to dust-control use in these trades.

Based on the percentage of participants reporting their firm usage rate as either “always” or “regularly”, the rates of usage of methods of asphalt fume control in roofing are ventilated/insulated kettles (28.1%), mechanized asphalt spreaders (26.5%), low-fume asphalt material (20.5%) and tanker delivery systems (6.5%). Respondents did not have a very high perception of the risk to worker health associated with asphalt fume (12.5% strongly agree). The biggest motivator to adopt fume control technologies was worker safety (76%). The biggest barrier to adoption was cost (83%).

Translation of Findings

The findings of this work can be directly applied to improve construction safety and health. To improve worker and contractor willingness to use safety equipment, training interventions can be developed based on the findings of these studies, in the following ways. Training should emphasize the health risks associated with the work. The findings of this work can also inform future research investigations in several ways. The information about current usage trends, perceptions of risks, barriers, and benefits of dust and fume control technology can be employed in the development of interventions to improve the use of these controls in concrete, masonry, and asphalt roofing trade sectors of the construction industry.

Outcomes/Impact

4. Potential Outcomes

The findings of this work could improve construction safety and health in construction practice in the following ways:

- Development of worker training guidelines
- Improved worker training
- Improved adoption of PtD innovations among workers and contractors

5. Intermediate Outcomes

The findings of this work have the potential to improve construction safety and health management:

- Safety management programs should incorporate the findings of this work
- The trade associations for concrete, masonry, and asphalt roofing have agreed to publish these findings in their trade publications
- The trade journal, Professional Safety, has accepted an article for publication, thus disseminating this work to safety professionals
- Future research is currently underway to develop similar interventions for concrete, masonry, welding, and asphalt roofing trade sectors

6. End Outcomes

The PtDAR project has begun to see some notable impacts:

- The Occupational Safety and Health Administration (OSHA) cited this work in its recent advisory document regarding the control of silica in construction operations.
- Environment Canada has cited this work in a draft regulation regarding quartz exposures.
- The PI was invited to speak at Purdue University's annual event, "The Engineer of 2020" on PtD in engineering design.
- Publications are in review by the Journal of Construction Engineering and Management of the American Society of Civil Engineers.

Section II: Final Progress Reports by Subproject (Scientific Report)

Project ID 644 - Novel Optical Systems for Real-Time Welding Fume Monitoring

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Abbreviations

AD	Aerosol density
CCD	Charge-coupled device
NORA	National Occupational Research Agenda
OSA	Optical spectrum analyzer
PS	Polystyrene
Q	Quality
SEM	Scanning electron microscope
SMF	Single-mode fiber
WGM	Whispering gallery mode

Abstract

Project Title: Novel Optical Systems for Real-Time Welding Fume Monitoring

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The NIOSH-funded project is entitled “Novel optical systems for real-time welding fume monitoring”. As the title suggest, the central goal of this project is to develop three types of optical system capable of real-time monitoring of the welding process.

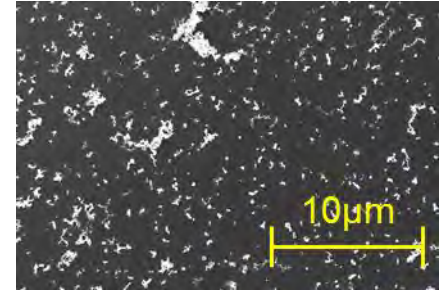
The most significant discovery of this project is the demonstration of a miniature optical sensor that can detect the presence of nanoscale aerosols generated by the welding process with extremely high sensitivity. The sensor is based on widely available commercial silica fiber. For the purpose of welding aerosol sensing, such a fiber can simply be regarded as a dielectric cylinder, which, due to optical reflection at the silica interface, can confine optical signals along the surface of the cylinder in the form of a whispering gallery mode (WGM). If the silica fiber surface is free of welding aerosols, due to the extremely smooth silica interface, light can circulate within the silica cylinder for a very long distance. Correspondingly, the WGM produces a sharp spectral dip in its transmission spectrum. If, on the other hand, the surface of the silica fiber is attached with welding aerosols, the aerosols can scatter light towards different directions and therefore change the transmission characteristics of the WGM. Experimentally, we find that the presence of welding aerosols can induces a measurable shift in the position of the WGM transmission dip. Through extensive experimental studies, we have established a unique link between the measured WGM resonance shift and the amount of welding aerosols collected on the silica fiber surface. This novel optical system differs from existing systems in three aspects. First of all, it is extremely sensitive and can detect welding aerosols with total mass as low as 1-10 ng. Secondly, our optical system can detect nanoscale aerosols. In our experimental studies, the size of welding aerosols is typically in the range of 50 to 100 nm. Lastly, the size of our optical sensor can potentially be made to be very small and its cost very low. This is mainly because we choose the most commonly available silica fiber as the sensor itself, which possesses very small fiber diameter (125 μm) and very low cost. We anticipate that such a sensor can play an important role for improving the health of construction workers where the presence of harmful nanoparticles poses significant health concerns.

Additionally, we have also built an optical emission spectroscopy system that can measure the spectral components of light produced by the welding process. We have identified individual emission peaks associated with elements such as Ni and Cr and tested such an optical system using welding materials with different composition. Finally, we have also built a Raman spectroscopy system capable of detecting the composition of a micron-scale particle, in both a free space configuration as well as a fiber-based approach compatible with the WGM-based sensor presented above.

A. Section 1

A.1. Significant (Key) Findings

The most significant finding of this project is the demonstration of an optical system capable of detecting the presence of nanoscale welding aerosols with high sensitivity. Such a sensing system directly addresses aim 2 of the project, where we propose to use the scattering of light by welding aerosols for optical sensing. To facilitate future translation into practical construction practices, in designing such a sensing system, we have taken the following factors into consideration. First of all, we require that the sensor itself must be miniature in size, readily available, easy to fabricate and calibrate, inexpensive, and capable of achieving high sensitivity. To satisfy these requirements, we choose to use silica-based fiber devices that can support high quality (Q) factor whispering gallery modes (WGMs). Theoretically, the existence of WGMs can be attributed to the simple fact that silica-based fiber devices tend to possess extremely smooth surfaces with minimal scattering. Therefore, if we use such a silica-based device as our sensor, due to the almost complete light reflection at the silica interface, optical signals can travel along the sensor surface for a long distance with minimal loss. A direct consequence is that by measuring the transmission of optical signals through such a sensor that supports high-Q WGMs, we can readily identify multiple sharp transmission dips, where each dip corresponds to a specific WGM. Using a commercial silica fiber as the sensor, we have developed a protocol that allows us to reliably identify a specific WGM for aerosol sensing. Perhaps more importantly, we find that if the sensor surface is accumulated with welding aerosols, the transmission dip associated with the aforementioned WGM would shift. After extensive experimental characterization, we have established an empirical relationship that links the WGM resonance shift with the amount of welding aerosols accumulated onto sensor surface. Then, by measuring the resonance shift in real time, we should be able to achieve WGM-based welding aerosol sensing.



After extensive experimental characterization, we find our WGM-based sensor design has three distinct advantages. First of all, it is significantly more sensitive than existing approaches that are based primarily on cascade impactors. In existing impactor design, one must first collect sufficient welding aerosols before one can use a microbalance for mass measurements. Typically, the mass of collected aerosols must exceed 1 μg . In contrast, we estimate that our WGM-based design can detect welding aerosols with total weight as low as 1-10 ng. Secondly, the WGM-based system can detect nanoscale welding aerosols. In the figure above, we show a scanning electron microscope (SEM) image of welding aerosols that can be detected using our fiber sensor. The diameters of the welding aerosols shown in the figure are mostly below 250 nm, and typically vary in the range of 50 to 100 nm. Finally, the WGM fiber sensor itself is small (125 μm in diameter and < 2 cm in length), widely available commercially, and cost very little (less than \$1). We anticipate that these unique features of our WGM-based sensor design should greatly facilitate practical translation.

Next, we have constructed a low cost spectroscopy system capable of measuring the emission spectra of light generated by the welding process, which is our aim 1. Using this system to monitor a typical welding process in real time, we find multiple peaks in the captured emission spectra and identified several peaks characteristics of elements such as Cr and Ni. For additional verification, we find that we can use the measured emission spectra to identify welding rods / work pieces that contain elements such as Cr and Ni.

Finally, we have established two different optical systems for Raman spectroscopy, which is the goal for aim 3. One of the two systems is based on free space optics, where we have demonstrated that we can detect the presence of a single micron-sized particle attached to a silica fiber taper. The other system

relies on the existence of WGM for sensitivity enhancement. The principle has been demonstrated using a silica fiber ring structure that supports WGMs.

A.2. Translation of Findings

First of all, the results obtained during our experimental study suggest that the silica-fiber-based WGM sensor can be directly used for nanoscale aerosol sensing, which is becoming increasingly important in construction practices.

Additionally, given the ultra-high sensitivity of the WGM-based aerosol sensor, it can also find applications that complement existing construction practices. For example, in current cascade-impactor-based approach, one must “artificially” pump air through the cascade impactor for aerosol collection. And in order to collect sufficient amount of aerosols for weight measurements, the total volume of air pumped through the impactor must be sufficiently large. In contrast, for our WGM-based aerosol sensor, due to its high sensitivity, such practice is no longer necessary. In fact, in our current experiments, we simply let the welding aerosols naturally drift towards the fiber sensor and become adsorbed onto sensor surface, with no “artificial” air flow at all. As such, we find a highly relevant phenomenon, which is the fact that the majority of welding aerosols attached to the fiber sensor are nanoscale in sizes, with aerosol diameter typically less than 250 nm. A likely explanation is that without “artificial” air flow, smaller aerosols (i.e., those that are nanoscale in sizes) are more likely to drift further and be captured by the fiber sensor. If, on the other hand, we were to utilize a cascade impactor for aerosol collection and analyses, we must sample a sufficiently large air volume, and may not be able to discover the dominance of nanoscale aerosols in regions further from the welding arc. In summary, our fiber-based aerosol sensor should enable researchers to map the distribution of nanoscale aerosols without any external perturbation in the form of “artificial” air flow for aerosol sampling and collection.

It is also worthwhile to point out that due to the low cost of the silica-fiber based WGM sensor, it is feasible to deploy a large number of such sensors at multiple locations within a construction site for real-time distributive sensing, i.e., measuring aerosol concentrations at multiple locations. If desired, we can also deploy the optical emission spectroscopy and the Raman spectroscopy system to provide information on aerosol composition. Due to the size and cost of these two systems, however, it may not be feasible for multipoint monitoring.

A.3. Outcomes / Impact

The optical systems developed here can generate significant potential outcomes in the following areas.

- (1) The development of nanotechnology has made it increasingly important to monitor the presence of nanoscale particles in work places and construction sites. The silica-fiber-based WGM sensor that we developed for welding aerosol monitoring is well suited to meet such demands.
- (2) The ultrahigh sensitivity of the WGM sensor is also relevant for applications that require sensitivity that exceeds the capability of existing cascade-impactor-based approaches.
- (3) By multiplexing multiple low cost WGM sensors together in a fiber optic network, we should be able to simultaneously monitor aerosol concentrations at multiple sensing locations in real time. No existing cascade-impactor-based particle sensing technology is capable of this functionality. Therefore, the adoption of our technology can open up new avenues of investigation. For example, with our WGM sensor based technology, it is now possible investigate, in real time, whether nanoscale aerosols are homogeneously or heterogeneously distributed throughout a specific construction site.
- (4) Minor modifications of sensor design may enable us to tailor these optical systems for different types of sensing applications.

B. Scientific Report

B.1. Background

The National Occupational Research Agenda (NORA) has identified exposure to welding fumes as a major health hazard affecting construction workers. Numerous studies have shown that extended exposure to welding fumes can significantly increase the risk of tuberculosis, bronchitis, airway irritation, lung cancer, and other diseases. Furthermore, the health impact of welding aerosols may significantly depend on their size and chemical composition. Current techniques for monitoring welding aerosols require collection of aerosol samples using filters and cascade impactors, then characterization of the collected samples using bulky instruments such as a microbalance or an aerosol mass spectrometer. Consequently, current methodologies make it very difficult to monitor the presence of welding aerosols in construction sites in real time with high sensitivity. Additionally, the challenge of real-time, high sensitivity aerosol sensing is even more problematic when particles are less than 100 nm in diameter. Yet, numerous studies suggest that such nanoparticles are associated with the most significant health risks. The overall objective of this project is to develop optical systems capable of addressing these challenges.

B.2. Specific Aims

This project contains three specific aims. Each aim corresponds to a specific optical system, as listed below:

Aim 1: Optical Emission Spectroscopy System Development and Validation

Aim 2: Optical Scattering System Development and Validation

Aim 3: Raman Spectroscopy System Development and Validation

These three aims are independent of each other. Therefore, our research on the three aims is separately discussed below. Due to the importance of aim 2, the development and validation of optical scattering system capable nanoscale welding aerosol sensing is first discussed in section B.3.

B.3. Development and Validation of an Optical Scattering System based on High-Q WGMs (Aim 2)

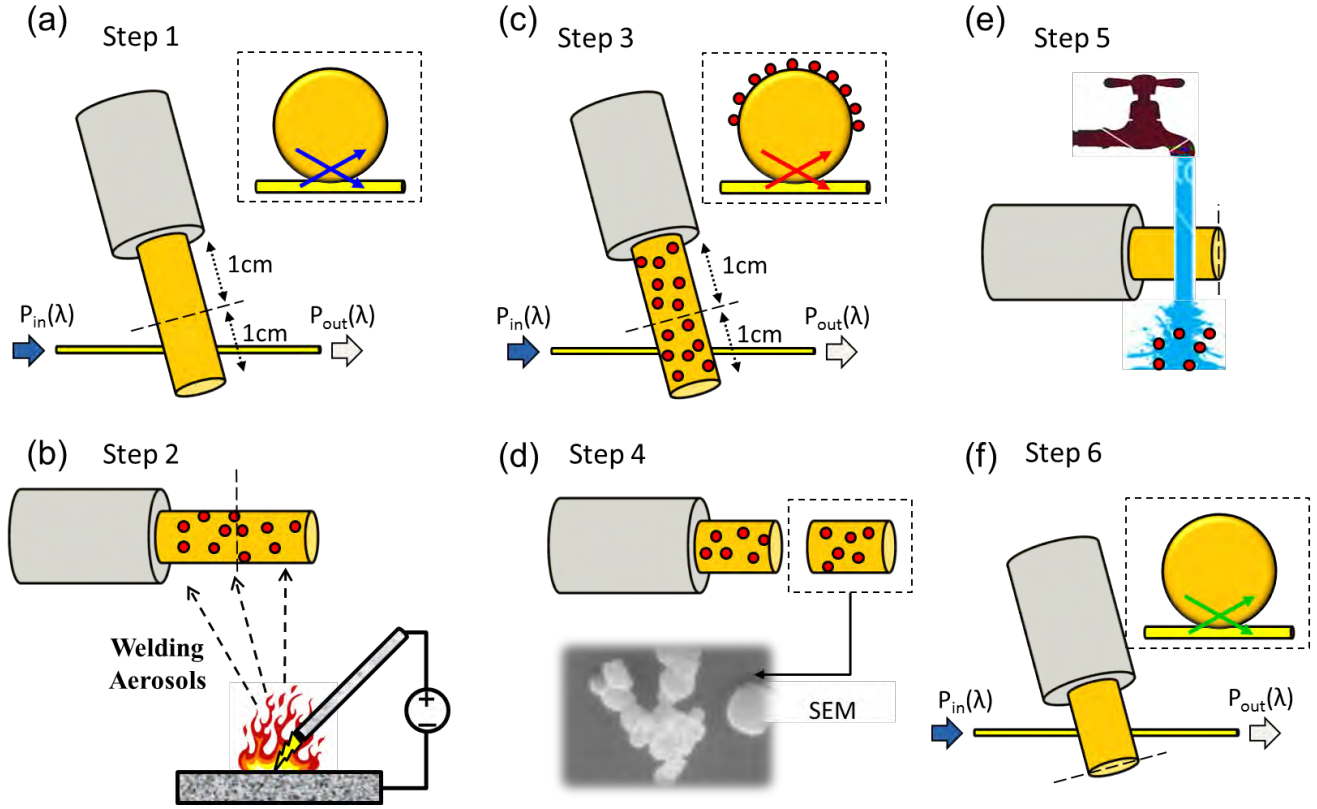


Fig. 1. Methodology in our WGM-based aerosol characterization procedure. The process is divided into six steps: (a) clean fiber sample measurement, (b) welding aerosol deposition, (c) aerosol-covered sample measurement, (d) SEM analysis, (e) aerosol removal, (f) control measurement of the re-cleaned fiber sample.

B.3.1. Methodology

The main goal of this study is to demonstrate the feasibility of using WGMs in a cylindrical resonator to detect the presence of nanoscale welding aerosols. In this section, we provide a general description of our characterization procedure. Experimental results that are obtained using this procedure are presented afterwards. Fig. 1 illustrates major steps in our characterization procedure, which can be naturally divided into: (a) clean fiber characterization (step 1), (b) welding aerosol deposition (step 2), (c) measurement of the aerosol-covered fiber sample (step 3), (d) SEM imaging of the aerosol-covered sample (step 4), (e) sample cleaning / aerosol removal (step 5), and (f) measurement of the cleaned fiber sample for control experiment (step 6).

Step 1, which is the characterization of WGMs circulating within a clean cylindrical fiber, is carried out by measuring transmission spectra through a thin fiber taper ($\sim 1 \mu\text{m}$ in diameter) coupled with the cylindrical resonator, as illustrated in Fig. 1(a). The transmission spectra of the coupled taper-resonator system may depend on many parameters including taper profile, coupling location, taper-resonator coupling angle, silica fiber diameter, and the specific WGM under consideration. In order to quantify the impact of these parameters, a detailed study of clean silica resonators is carried out and the results are presented in the next section. Here we only mention the steps we take to minimize measurement uncertainties, which are: (1) all experimental studies reported here are carried out using the same fiber taper; (2) all taper-

resonator coupling measurements are performed at the same taper location; (3) all measurements are based on the same WGM with resonance wavelength in the vicinity of 1522 nm; (4) any uncertainty due to variations in cylinder diameter is accounted for by measuring WGM resonance wavelength prior to aerosol deposition onto the resonator.

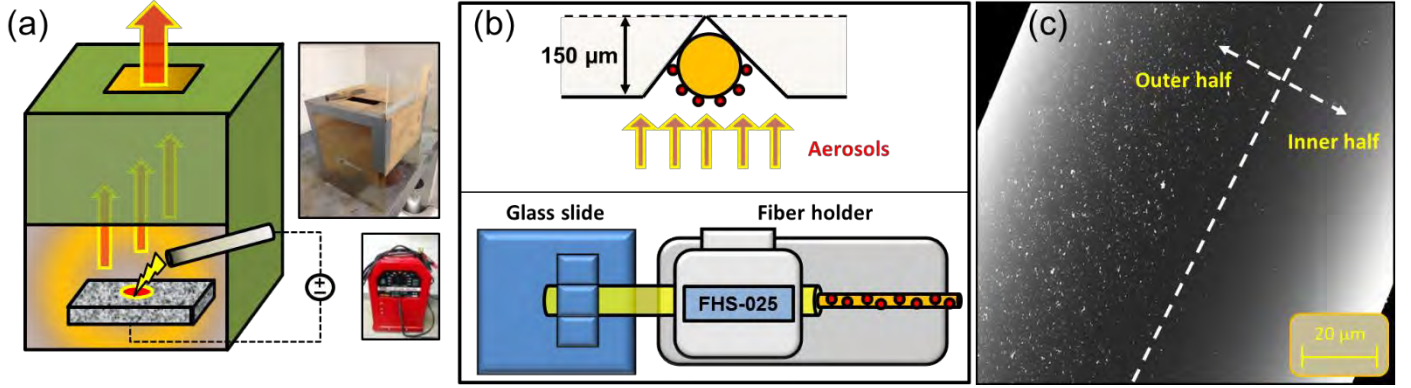


Fig. 2. (a) Illustration of the welding aerosol deposition system (Insets: welding chamber and arc welder at top-right and bottom-right corner, respectively). (b) The fiber-based WGM resonator is placed in a V-groove such that only the outer half of the resonator surface is exposed to the welding aerosols. The surface of the inner half is covered by the V-groove and remains clean. The clean inner half is used for taper coupling and WGM transmission measurements. (c) A representative SEM image of the aerosol-covered sample (side view), which shows both the aerosol-covered outer half and the clean inner half.

The setup for step 2, welding aerosol generation and deposition, is illustrated in Fig. 2(a). To control the flow of welding aerosols, we construct a welding chamber using acrylic plates to ensure that aerosols generated by the welding process exits through an outlet at the top of chamber. The welding aerosols are generated by electric arc welding, where we utilize an electric current supply (AC-225 Arc Welder, Lincoln Electronic) to produce electric arc between an electrode (E6011 Fleetweld 180-3.2mm, Lincoln Electronic) and a working piece (stainless steel plate) placed at the bottom of welding chamber. The electric arc is generated by electrical discharge through ionized gas using 105 A direct current that melts the metal. This process is naturally accompanied by the production of welding aerosols. These welding aerosols naturally drift through the chamber outlet at the top and are deposited onto the resonator surface. Unlike the traditional aerosol collection methods, which are based on cascade impactors and require high speed air flow, our approach does not need any air pump or forced air flow for aerosol collection.

Throughout the entire process of aerosol collection, the fiber resonator is placed in the V-groove of a fiber holder (FHS-025, Sumitomo Electric), which itself is fixed at the outlet of welding chamber and facing downwards, as shown in Fig. 2(b). This configuration ensures that only the outer half of the resonator surface is exposed to air flow and available for aerosol deposition. The remaining resonator surface (i.e., the inner half), hidden by the V-groove, should remain clean and free of aerosols. This expectation is clearly confirmed by the SEM image in Fig. 2(c), where the side view of the aerosol-covered sample clearly shows both the aerosol covered outer surface and the clean inner surface. Our experiments require samples with different amount of aerosol deposition. This is achieved by either controlling the amount of welding rods consumed in the process or by adjusting the total welding time. All other welding parameters remain the same. Thus, statistically speaking, the size distributions of aerosols produced by this process should remain similar. After aerosol deposition, we fix the aerosol-covered sample onto a glass slide before we release the sample from the fiber holder. This procedure, illustrated in Fig. 2(b), allows us to readily distinguish the aerosol-covered outer surface from the clean inner surface.

Next, we proceed to step 3, where we utilize the same fiber taper and the taper-based coupling system to measure transmission spectra of the aerosol-covered sample. In this process, we always make sure

that the aerosol-covered surface remains further away from the fiber taper, and that only the aerosol-free surface can possibly touch the taper during our measurements. As a result, we eliminate the possibility of inadvertently transferring welding aerosols from fiber surface to the taper. As such, the taper remains clean and can be used for all experiments reported here. After WGM characterization, we take SEM images of the aerosol-covered sample in step 4. Here we simply cut the silica fiber resonator in half, and remove the section that has been used in WGM measurements for SEM imaging and analysis.

At the last stage, a control experiment is carried out to ensure that the fiber resonator remains the same throughout the entire WGM characterization procedure. Specifically, our goal is to exclude the possibility, however unlikely, that variations in WGM transmission spectra might be caused by physical or compositional changes to the silica fiber resonator. In this process, we first carry out step 5, where we remove welding aerosols from the surface of the remaining fiber resonator. (Recall that half of the aerosol-covered resonator is removed for SEM analysis and no longer available for this control experiment.) The cleaning procedure consists of wiping the sample surface with alcohol, rinsing it in water for 30 seconds, sonicating for 10 minutes, again washing in water for 30 seconds, drying in air for 10 minutes, and finally wiping the sample surface with alcohol. Then, in step 6, we again use the same fiber taper and coupling system to measure the transmission spectra of the cleaned fiber sample. If, after aerosol removal, sample transmission spectrum becomes indistinguishable from the one obtained prior to aerosol deposition, then any changes in the WGM transmission in the aerosol-covered sample must be attributed to the presence of aerosols only.

Altogether, 29 resonator samples, each with different amount of aerosol deposition, are characterized in our study. It is worth pointing out that these 29 resonators may possess slightly different cylinder diameters. Therefore, in our characterization procedure, individual resonators must be calibrated in advance and their transmission spectra must be measured before aerosol deposition. Clearly, characterizing WGM in a clean cylindrical resonator is a critical step in aerosol detection. In light of its importance, the experimental study of clean fiber resonators is described in the next section in details.

B.3.2 Results of Clean Resonator Characterization

The most significant advantage for using commercial silica fiber as the sensing resonator is that all resonator parameters are extremely well controlled. In this study, we choose to use standard single-mode fiber (SMF, Corning SMF-28), whose cladding diameter is precisely set at $d = 125 \pm 0.7 \mu\text{m}$. Since WGMs are mostly confined in the region near its air-silica interface, we can essentially treat the SMF as a uniform dielectric cylinder with refractive index approximately 1.45.

The tapers used for WGM coupling are fabricated from the same SMF-28 fiber by using our custom-built heat and pull system. We monitor taper optical transmission throughout the pulling process and use a computer program to ensure that the taper waist is approximately $1 \mu\text{m}$ in diameter. In the tapered region, by placing the cylindrical resonator in close proximity to the fiber taper, optical wave can be evanescently coupled into a WGM propagating around the circumference of the cylindrical resonator. To reduce variability in coupling strength, we always place the resonator in direct contact with the fiber taper. A CCD camera is mounted above the taper and the resonator, with its focal plane fixed at the coupling spot for visual monitoring. As shown in Fig. 3(a), we use an optical spectrum analyzer (si720, Micron Optics) to measure taper transmission in the wavelength range of 1520-1570 nm. The OSA is equipped with an internal laser source and a photo-detector in a single module. The resolution of the OSA is approximately 3-4 nm and is sufficient for identifying WGMs with relatively low Q factors of 10^5 or less, which is what we typically observe in our cylindrical resonators.

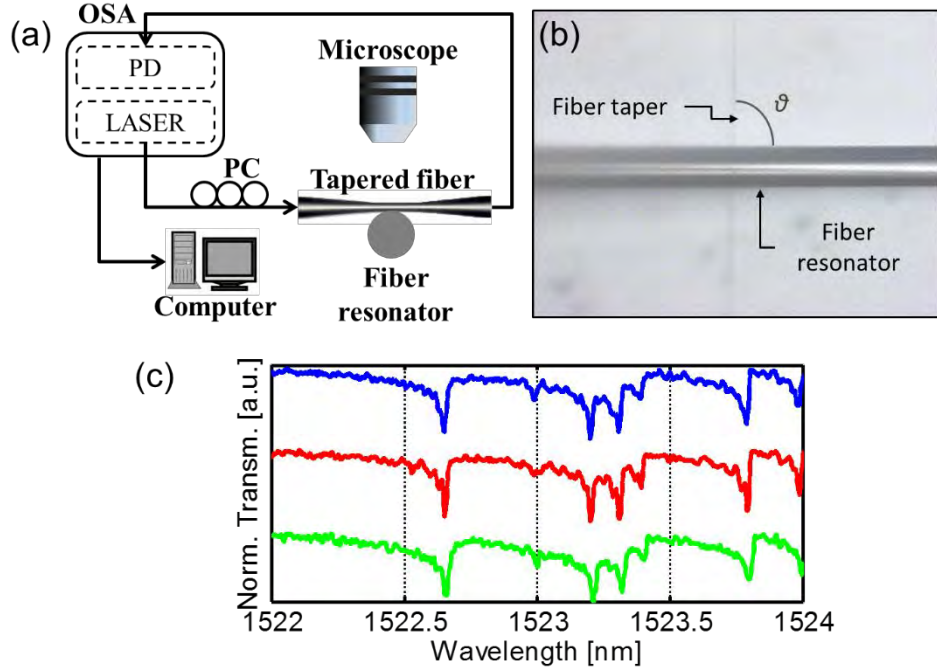


Fig. 3. (a) Illustration of the optical system for WGM transmission spectrum measurements. (b) Image of clean resonator coupling. (c) WGM transmission spectra measured under different alignment angles. (blue: 0 pm at $\theta=90^\circ$, red: 2.5 pm at $\theta=85^\circ$, green, 5 pm at $\theta=80^\circ$).

Besides taper-resonator gap distance (which is set at zero), the measured transmission spectra may also depend on the alignment angle and the location of taper-resonator coupling. Without using a computer controlled micro-positioner for fiber alignment, the angle between the fiber taper and the cylindrical resonator (denoted as θ in Fig. 3(b)) is unlikely to be exactly 90° . In previous work, it has been shown that a small amount of misalignment (i.e., $80^\circ < \theta < 90^\circ$) has no significant impact on the characteristics of WGMs in a cylindrical resonator. We have experimentally confirmed this conclusion. Fig. 3(c) shows several transmission spectra measured at the same taper location but under different alignment angle, where θ values are estimated based on CCD camera images. A WGM resonance can be clearly identified near 1522.7 nm and its dip position remains almost the same regardless of misalignment. For quantitative comparison, we extract the resonance wavelength and the Q factor of the WGM through Lorentzian fitting. In particular, the Q factor of the WGM is calculated by dividing the resonance wavelength with the full width half maximum (FWHM) of the transmission dip. From the fitting data, we can conclude that for small misalignment (i.e., $80^\circ < \theta < 90^\circ$), the resultant resonance shift is less than 5 pm, which is close to the intrinsic limit of our transmission measurements, imposed by instrument resolution.

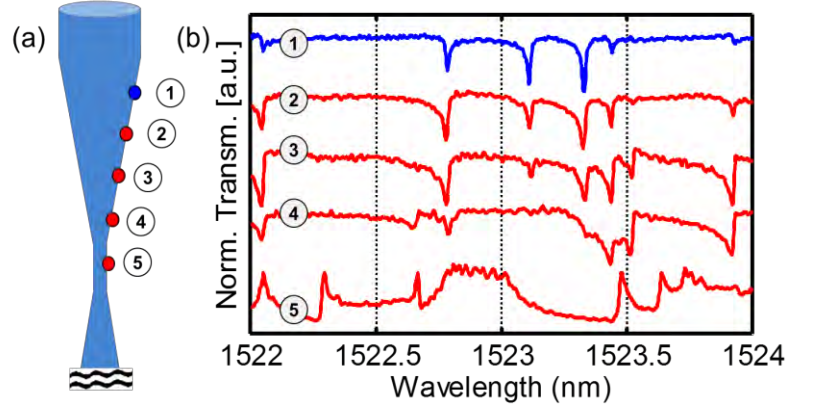


Fig. 4. (a) Illustration of coupling at different taper locations. (b) Transmission spectrums at each coupling location.

Next, we investigate the relationship between the measured transmission spectrum and the location for taper-resonator coupling. Fig. 4 shows five representative WGM transmission spectra, which are

obtained using the same cylindrical resonator in direct contact with the same fiber taper. The locations for taper-resonator coupling, however, are different. In Fig. 4(a), we illustrate the five different coupling locations. The transmission spectra that correspond to these five coupling locations are also labeled in Fig. 4(b) accordingly. As illustrated in Fig. 4(a), the 5th location is at the center of the fiber taper, where taper radius is the narrowest and taper-resonator coupling should be the strongest. The 1st location, on the other hand, is farthest from the taper center, which should correspond to the smallest taper-resonator coupling among the five locations. The rest of the coupling locations are in between. For location 1, 2, and 3, which possess relatively weak taper-resonator coupling, we can use Lorentzian fitting to determine the corresponding WGM resonance, which are respectively 1522.7869 nm (1st location), 1522.7817 nm (2nd location), and 1522.7826 nm (3rd location). Note that for location 1, 2, and 3, despite changes in taper-resonator coupling, the WGM resonance wavelength remains almost identical and varies only within a very small (~ 5 pm) bandwidth. Additionally, compared with data taken at the 1st location, the spectral line-shapes of WGM transmission obtained at the 2nd and 3rd location become asymmetric and contain more blue-shifted components. Similar line-shapes have been observed in previous work, and are attributed to spiral modes that propagate along the axial direction of the cylinder. For the 4th and 5th coupling location, we can no longer clearly identify the desired WGM resonance in the vicinity of 1522 nm. This phenomenon can be potentially explained by the over-coupling, where stronger waveguide-resonator coupling actually leads to a shallower transmission dip.

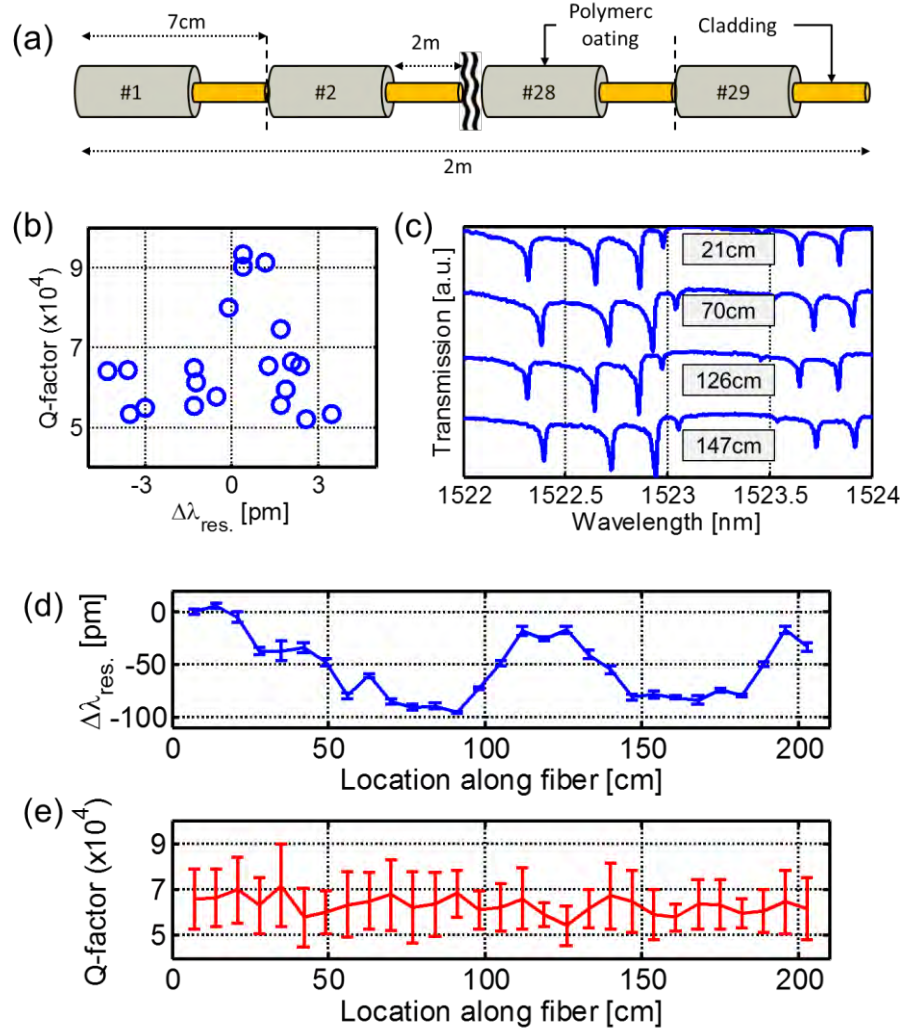


Fig. 5. (a) Preparation of clean fiber samples for WGM transmission measurements. All samples are taken from the ~2-meter spool of SMF-28 fiber. (b) The distribution of WGM wavelengths and Q factors of the 1st sample, measured at 20 randomly chosen locations along the cylindrical resonator (~ 1 cm in total length). (c) Representative transmission spectra measured at four different locations that are approximately 21, 70, 126, and 147cm away from the 1st sample, respectively. (d) WGM resonance wavelength and (e) Q factor of cylindrical resonator taken from different locations along the 2-meter spool of SMF-28 fiber.

In all following measurements, we select the 1st location, which leads to a symmetric WGM resonance in the vicinity of 1522 nm, as the taper-resonator coupling location for all experiments. To enforce this criterion, we fix the position of the microscope objective and the CCD camera in Fig. 4(a). We then mark the 1st coupling location on the CCD camera images, and always bring the fiber resonator to the marked location for transmission measurements.

Besides coupling angle and taper-resonator coupling location, we also characterize WGM properties of 29 cylindrical resonators, all taken from a single spool of SMF-28 fiber but at different locations. Refer to Fig. 5(a) for illustration. Specifically, we evenly divide a 2-meter long SMF-28 spool into 29 samples, with approximately 7 cm in length for all samples. (All 29 samples are later used for aerosol sensing experiments.) For each section, we remove approximately 2 cm polymer coating from one end and use the cleaning procedure described in section 2 to clean the sample for WGM measurements. (Refer to step 5 in Fig. 1.) For proper statistical analysis, for every cylindrical resonator, we record transmission spectra at 20 random spots within ~1 cm length. Only the WGM in the vicinity of 1522 nm is considered in our analysis. One reason for choosing this specific WGM is the relatively large spectral separation between this mode and its neighboring resonances, as can be seen from Fig. 5(b). In Fig. 5(c), we show four representative examples of bare fiber transmission spectra, obtained using samples taken at four different locations (approximately 21, 70, 126, and 147cm away from the 1st sample, respectively). Compared with the WGM resonance in the 1st sample, the resonance shifts of the four samples are respectively blue-shifted by -5.5, -85.6, -16.7, and -81.3pm, respectively.

For each of the 29 samples, the resonance wavelengths and the Q factors of the aforementioned WGM, averaged over 20 locations, are shown in Figs. 5(d) and 5(e). Note that the x axis in Fig. 5(d) is resonance shift, which is calculated by subtracting the resonance wavelength of the 1st sample from those of subsequent samples. The results in Figs. 5(d) and 5(e) clearly shows that the resonant characteristic along the 2 meter length of fiber can vary smoothly and slowly, where the average slope for resonance shift ratio is 2.13 pm/cm and the maximum slope is 4.79 pm/cm. Translating resonance shift to variation in fiber diameter, we find that for the spool of SFM-28 fiber, its diameter can slowly vary in the range of 0.17 nm/cm to 0.39 nm/cm. Also notice that the Q-factors of the WGM remain roughly the same, as can be seen from Fig. 5(e).

It is worthwhile to point out that the spectra in Fig. 4(b) and Fig. 5(c) are shifted a few hundred picometers from each other. This is because results in different figures are obtained using fibers that are tens of meters away from each other. This result is consistent with our previous conclusion that the diameter of the SMF-28 fiber should vary slowly and continuously along its length. Recall that according to product specification, the SMF-28 fiber diameter is $125 \pm 0.7 \mu\text{m}$.

B.3.3. Results of WGM Sensing

Our next step is to measure WGM properties in samples covered with welding aerosols. All 29 samples, already characterized in Fig. 5, are deposited with different amount of aerosol by following the procedure described in Fig. 1. The same fiber taper is used for all transmission measurements.

We use the characterization of a specific aerosol-covered resonator sample to provide a more detailed discussion of the measurement steps already illustrated in Fig. 1. For any given sample, we first strip away 2 cm of its polymer coating and clean the exposed silica surface using the cleaning procedure described in section 2 (i.e., step 5 in Fig. 1). Then, in step 1, we record the transmission spectrum of the clean resonator and extract the resonance wavelength and the Q factor of the desired WGM. As

described in the previous section, we perform transmission measurement at 20 randomly chosen locations, from which we can determine the average value of the resonance wavelength (λ_{res}^{clean}) and the Q factor (Q^{clean}) of the clean resonator. Afterwards, in step 2, we use the custom-built system illustrated in Fig. 2 to uniformly deposit welding aerosols onto the clean resonator. Subsequently, in step 3, we perform transmission measurements at 20 random locations to obtain the average resonance wavelength ($\lambda_{res}^{aerosol}$) and the Q factor ($Q^{aerosol}$) of the aerosol-covered resonator. As shown in Fig. 1, all 20 measurement positions are located within the 1 cm section, which are then taken for SEM imaging in step 4. A representative SEM image of the specific sample is shown in Fig. 6(d). Afterwards, in step 5, we thoroughly clean the remaining 1 cm long resonator to remove all attached aerosols. Finally, in step 6, we again measure the WGM resonance of the cleaned section at 20 randomly chosen locations and determine the average WGM wavelength ($\lambda_{res}^{control}$) and Q factor ($Q^{control}$) for this control experiment. We expect the values for $\lambda_{res}^{control}$ and $Q^{control}$ should be very similar to those of λ_{res}^{clean} and Q^{clean} . If this expectation is met, we can conclude that any change in WGM properties are due to the presence of welding aerosols only. In this case, we calculate the aerosol induced resonance shift using $\Delta\lambda^{aerosol} = \lambda_{res}^{aerosol} - \lambda_{res}^{clean}$. For the control experiment, we can similarly define a resonance shift as $\Delta\lambda^{control} = \lambda_{res}^{control} - \lambda_{res}^{clean}$. By measuring λ_{res}^{clean} for each sample and subtracting it from the measured $\lambda_{res}^{aerosol}$, we ensure that our measurement results are not influenced by the small variation in λ_{res}^{clean} , which can differ from sample to sample, as can be seen from Fig. 5(d).

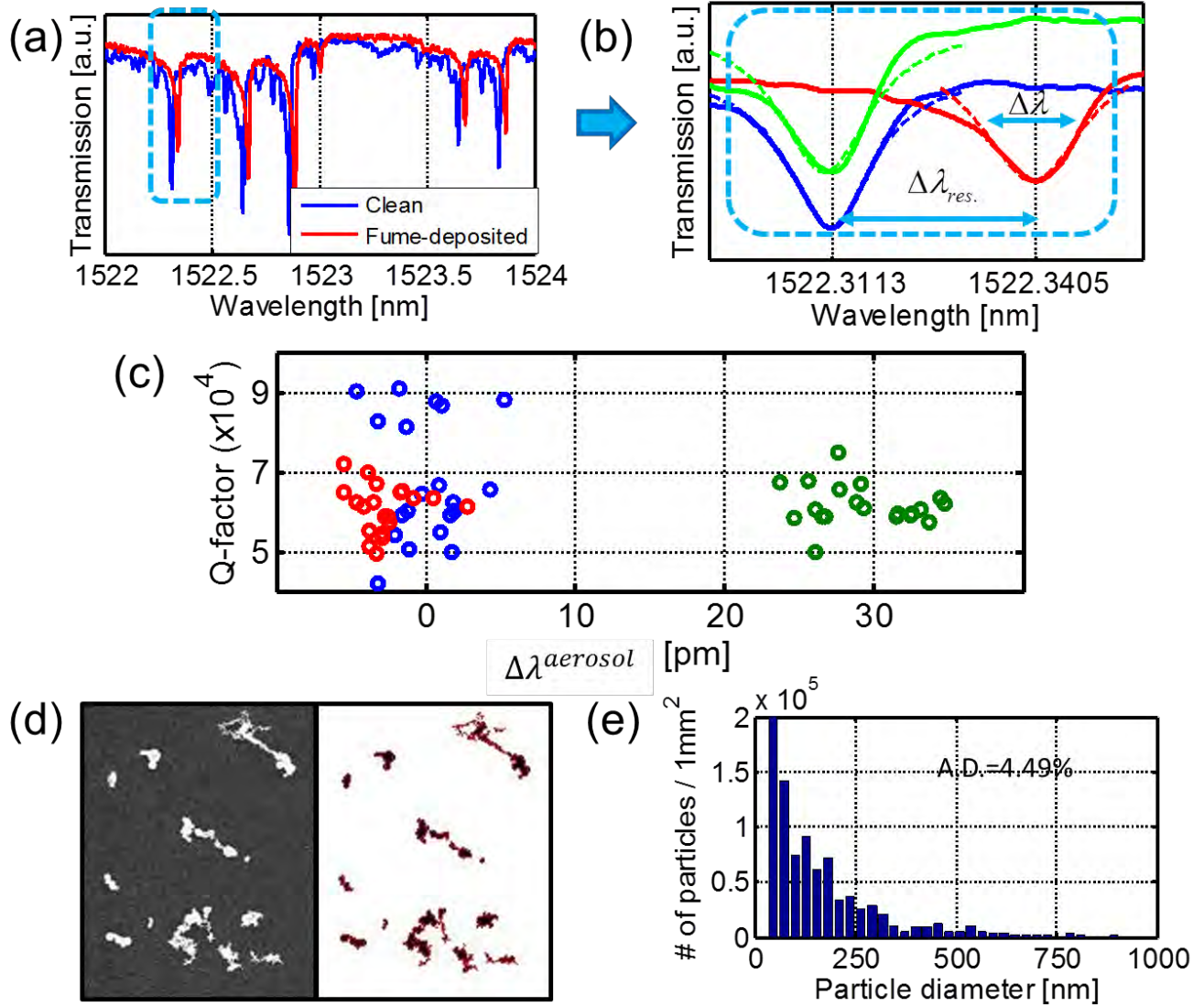


Fig. 6. (a) Two WGM transmission spectra measured from a fiber resonator when the resonator is clean (blue line) and when it is covered with welding aerosols (red line). (b) A magnified view of the WGM near 1522 nm. Blue line: clean resonator result; Red line: aerosol-covered resonator result; Green line: cleaned control resonator result. (c) The distribution of WGM resonance wavelengths and Q factors of clean (blue circles), welding aerosol covered (green circles), and cleaned control sample (red circles). (d) SEM image of the aerosol-covered sample surface (left) and the image processed with the edge-detection algorithm (right). (e) Statistical distribution of welding aerosols classified according to their equivalent diameter, with total aerosol density (A.D.) = 4.49%.

The experimental data obtained for a specific sample is summarized in Fig. 6. Fig. 6(a) shows two representative spectra, where the blue line corresponds to a representative measurement of the clean sample and the red line is obtained using the same sample but covered with welding aerosols. Clearly, the two transmission spectra are different. A magnified view of the transmission spectra near the desired WGM resonance is shown in Fig. 6(b), where we also add a green line that represent a control measurement. (The control measurement data is slightly shifted vertically to ensure that it can be distinguished from clean sample transmission.) Again, we observe that the WGM in the aerosol-covered sample is red-shifted in comparison to the clean sample WGM. Additionally, after aerosol cleaning, the WGM in the control sample is very similar to the WGM in the original resonator. These two conclusions also hold statistically. In Fig. 6(c), we show the resonance wavelengths and the Q factors of the same

WGM in the clean resonator, the aerosol-covered resonator, and the control resonator after aerosol removal. All 20 random measurements are shown for clean resonator, aerosol-covered resonator, and control resonator measurements. Based on Fig. 6(c), we can conclude that aerosol deposition produce a measurable red-shift that is statistically significant and much greater than measurement errors / system limitations. Specifically, after aerosol deposition, the WGM resonance experiences a red-shift of $\Delta\lambda^{aerosol} = 29.3$ pm. For the control experiment, we find that the WGM resonance after aerosol removal recovers the original value, and that the spectral shift between the control and the clean resonator is very small, i.e., $\Delta\lambda^{control} = -2.8$ pm, which is less than system resolution. The average Q factors of the clean, aerosol-covered, and control resonator are $Q^{clean} = 6.78 \times 10^4$, $Q^{aerosol} = 6.16 \times 10^4$, and $Q^{control} = 6.08 \times 10^4$, respectively. We observe that statistically speaking, the shift in resonance wavelength is much more pronounced than changes in WGM Q factors.

SEM image of the aerosol-covered resonator surface, taken in step 4, is shown in Fig. 6(d). The left panel is the original SEM image, whereas the right panel shows the image after application of edge-detection function in MATLAB. We apply this function to define the boundaries of aerosols in the image and then calculate the total number of pixels inside these particle boundaries. Based on the SEM images, we define aerosol density (A.D.) as the total sum of pixels within the particle boundaries divided by the total image pixels. We can also use the same edge detection method to estimate aerosol sizes. Specifically, we assume all particle shape to be a perfect circle. For each particle, we estimate aerosol diameter by equating aerosol area, which is the total number of pixels within the aerosol boundary, with the area of a perfect circle. For each resonator sample, we record SEM images at 10 random locations across regions covered by aerosols and use the 10 images to obtain average aerosol density and aerosol size distribution. For the sample shown in Fig. 6(d), the aerosol density is $A.D. = 4.49\%$. Correspondingly, its aerosol size distribution is shown in Fig. 6(e).

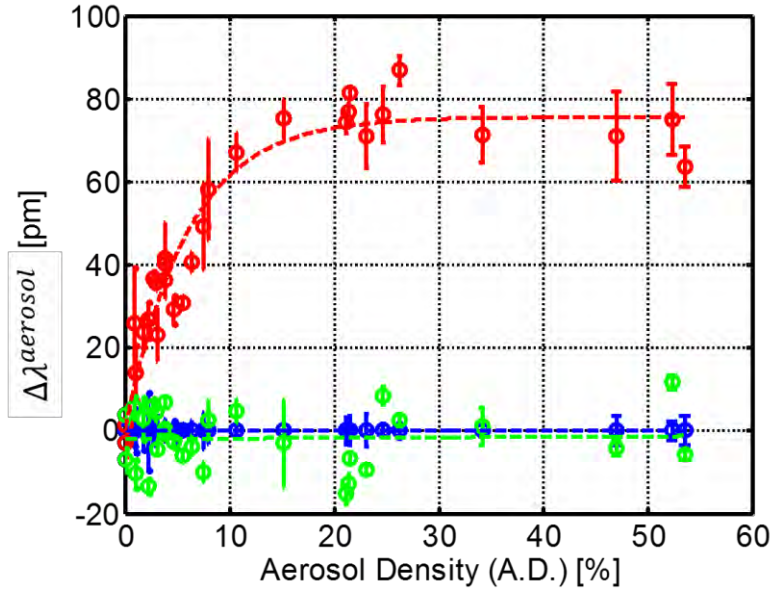


Fig. 7. The relationship between the WGM resonance shift obtained through optical measurements and the average aerosol density determined through SEM measurements (red circles). The blue and green circles represent initial characterization and control experiments, and should be close to zero, as shown in the figure.

The procedure described above allows us to quantitatively link the relationship between the measured WGM resonance shift ($\Delta\lambda^{aerosol}$) and the average aerosol density adsorbed onto the surface of the WGM resonator (A.D.). Fig. 7 shows the results we obtained for all 29 samples, each with different amount of welding aerosol deposition. We note that the results in Fig. 7 suggest a definite link between WGM resonance shift and the amount of aerosols on resonator surface. Empirically, we find a definite relationship between the aerosol induced resonance shift ($\Delta\lambda^{aerosol}$) versus aerosol density (A.D.), as described by the following fitting formula

$$\Delta\lambda^{aerosol} = 75.57 \cdot [1 - \exp(-0.1673 \times A.D.)] \text{ (pm)}.$$

We can regard Fig. 7 and the empirical formula given above as the most important result of this project. In Fig. 8, we shows four representative SEM images of resonator samples with different amount of welding aerosol deposition: (a) with no deposition (A.D.=0%), (b) one with 40.6 pm resonance shift (A.D.=6.4%), one at near saturated 75.1pm resonance shift (A.D.=15.2%), and one with saturated 75.1pm resonance shift (A.D.=52.3%).

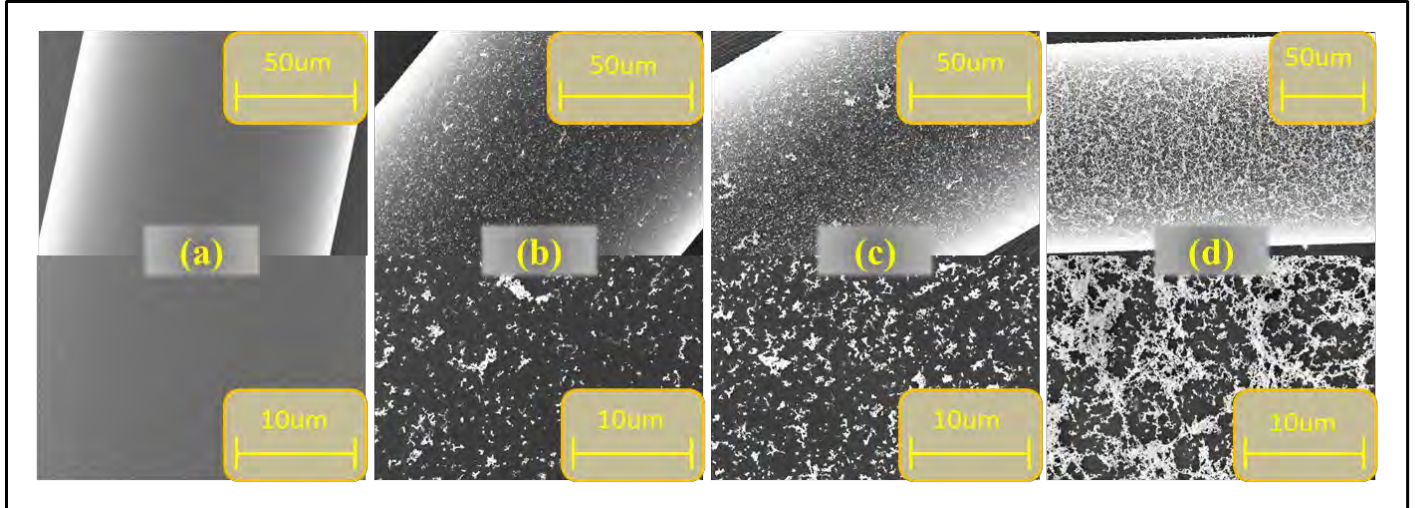


Fig. 8. Representative SEM images of resonator samples with different amount of average aerosol density (A.D.). First row: low magnification, Second row: high magnification.

B.4. Raman Spectroscopy System (Aim 3)

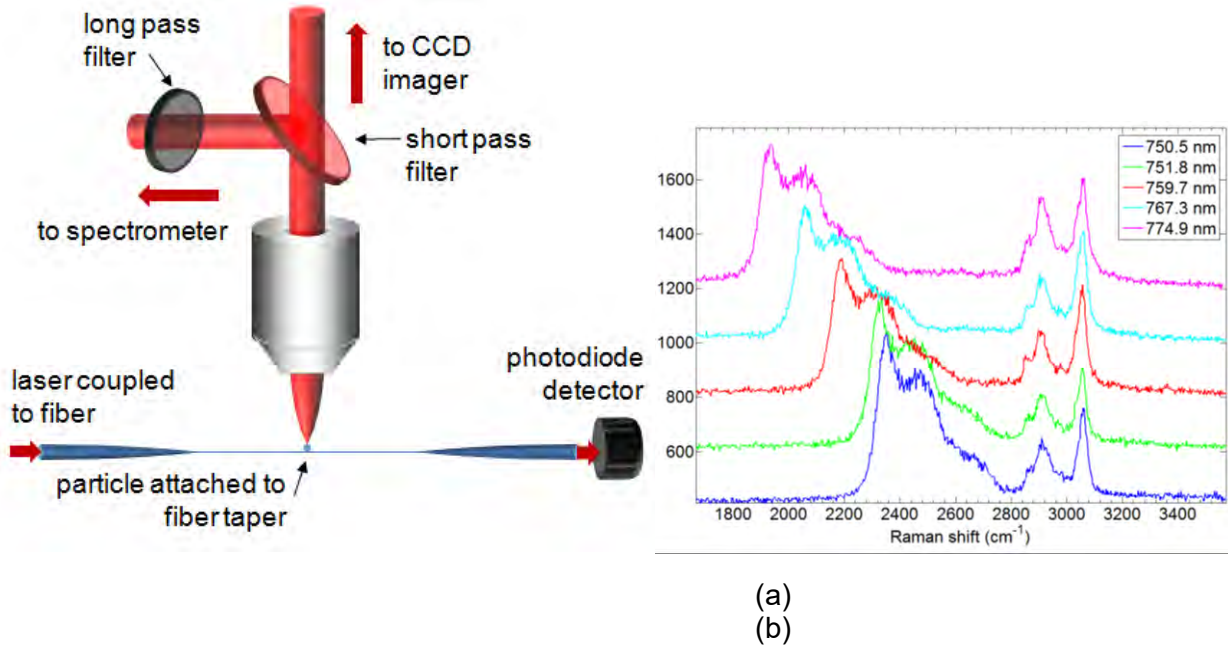


Fig. 9 Fiber taper based particle sensing (a) Schematic diagram of the setup (b) Raman spectra from a single 2- μm sized polystyrene microsphere measured by using different pump wavelengths.

We have also explored fiber tapers for Raman spectroscopic sensing, which provide a unique platform as fiber tapers can guide light and offer the opportunity for extended inelastic interaction of the evanescent field with adsorbed particles. Since Raman spectroscopy probes the “fingerprint” like vibrational response, it has high specificity and can be potentially a powerful tool for welding fume particle sensing. In addition, the fiber taper implementation also makes it possible to combine Raman spectroscopy with other sensing modalities, such as the WGM sensing technique for multimodal welding particle sensing. To overcome the low sensitivity of Raman spectroscopy, in this program we have also investigated the feasibility of using a fiber ring cavity to enhance the Raman signal.

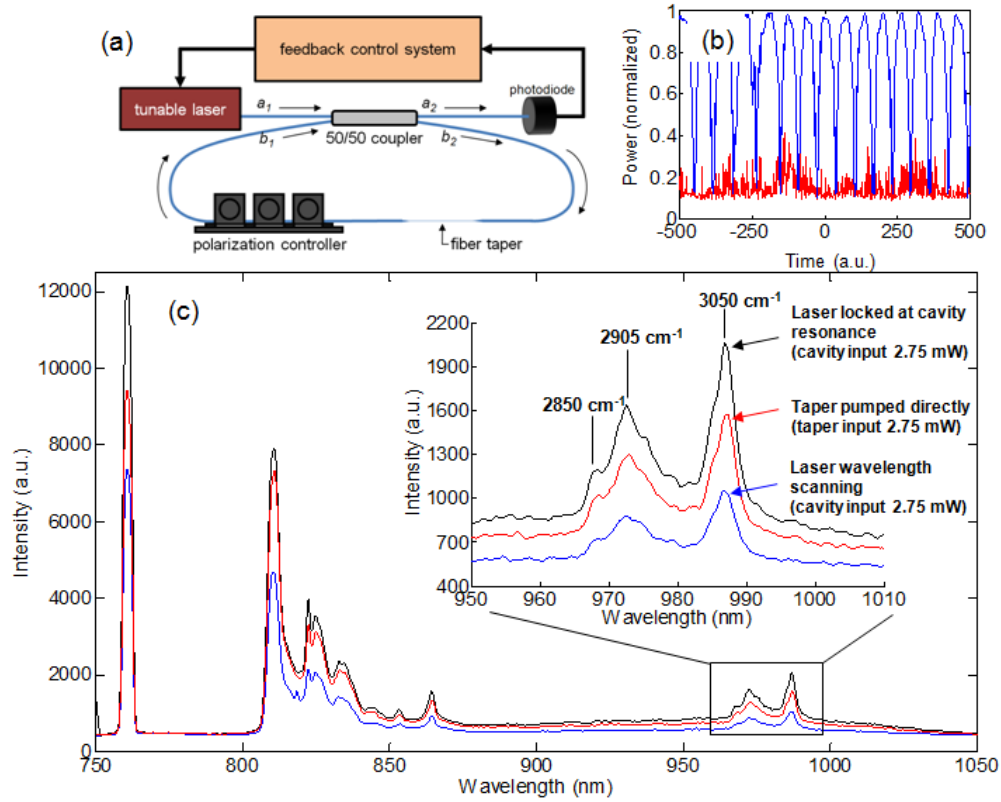


Fig.10 (a) Schematic of fiber ring resonator and wavelength locking setup. The fiber ring resonator is composed of a 50/50 fiber coupler, the fiber taper, and a polarization controller. (b) Comparison of locking (red) and unlocked transmission time-series plots (blue). The unlocked time-series was acquired while wavelength scanning. In(c), comparison of Raman spectra is shown for a 2 μm PS sphere attached to a fiber taper for the cases of wavelength locking (black), laser wavelength constantly scanning in the cavity configuration (blue) and taper only excitation (red). Each spectra was recorded using 2.75 mW input power and 30 second integration times.

The experimental setup is shown in Fig. 9 (a), where a tapered optical fiber is positioned with the taper waist located at the foci of a micro-Raman imaging and signal collection system. The fiber taper is fabricated by heating a single mode optical fiber with a hydrogen torch and pulling it through computer controlled translational stages. A tunable laser (Thorlabs TLK-L780M) is coupled to the fiber taper and a photodiode is used to monitor the transmission through the fiber taper. The micro-Raman imaging and signal collection system is confocal, and uses a long working distance objective lens (Mitutoyo 50x Plan Apo) to collect the scattered signal from a particle adhered to the fiber taper. A short pass filter is used to reflect scattered Raman signal to a spectrometer and a long pass filter is positioned in front of the entrance slit of the spectrometer to filter any residue pump laser light. In Fig. 9 (b), Raman spectra obtained from collecting the scattered signal from a 2 μm polystyrene (PS) microsphere attached to a fiber taper is shown. The characteristic Raman feature of interest for PS is located at approximately 3060 cm^{-1} . To demonstrate the collected signal is Raman generated from the PS microsphere, several plots

are shown in Fig. 9 (b) where the pump laser was tuned to several wavelengths between 750 and 775 nm and signal was acquired on the spectrometer with integration times of 30 seconds. Thus, the figure shows while the wavelength of the pump laser is tuned, the Raman shift for each PS peak remains the same at around 3060 cm^{-1} . The peak near 2950 cm^{-1} is a weaker, secondary PS peak overlaid by a broad background signal generated by the fiber taper. Additionally, the broad background peaks observed before 2000 cm^{-1} occurs from the presence of a strong silica Raman scattering background that is generated from within the fiber taper, which peaks at around 440 cm^{-1} (i.e., 13.2 THz). The long-pass filter (cut-off wavelength 900 nm) used in these results filters, in addition to the pump laser, most of the broad silica background. The existence of the background may limit the sensitivity when measuring low-frequency vibrational modes. Since the microsphere used in our study is relatively large, forward scattering is strong. For this reason, the microsphere was placed on the side edge of the fiber taper and Raman signal was collected in the upright direction to suppress the scattered silica Raman background. The scattered silica background is expected to decrease much faster than the Raman signal as particle size reduces.

Unlike in traditional Raman spectroscopy implemented by using a free-space excitation beam, the use of a fiber taper for guiding the pump laser field naturally creates a unique opportunity to “recycle” unused pump power by incorporating the taper into a fiber ring resonator. The power of a resonant mode circulating inside the ring cavity can be enhanced, leading to enhanced Raman scattering from an adhered particle and thus improved sensitivity.

As shown in Fig. 10 (a), we have developed a fiber ring resonator which consists of a 50/50 fiber coupler (Thorlabs FC-780-50B, measured 53/47 ratio at $\lambda = 761\text{ nm}$) for coupling the tunable laser to the cavity, a fiber taper, and a fiber polarization controller used to compensate for fiber birefringence in order to maintain the polarization state after each round trip. A photodiode is used to monitor the transmission and provides feedback signal to lock the laser to a resonant frequency of the fiber cavity. By modulating the laser frequency and simultaneously detecting the transmission signal with a lock-in amplifier, the slope of the transmission spectrum can be determined. A control signal is then applied to the tunable laser to lock its frequency to the minimum transmission position (i.e., zero slope), at which a resonator mode is excited. Demonstration of the frequency locking is shown in Fig. 10 (b), where a $2\text{-}\mu\text{m}$ polystyrene (PS) microsphere is adhered to the fiber taper. The blue curve plots the transmission signal as the laser frequency is scanned by a piezo actuator before the locking mechanism is activated. The figure shows several resonant modes that span multiple free spectral ranges of the fiber cavity. We then activate frequency locking using the configuration shown in Fig. 10 (a). The transmission signal is locked near its minimum value as is shown in the red curve of Fig. 10 (b), indicating the excitation of a resonant mode. After locking the laser to the resonance of the ring-cavity, we investigated the fiber ring resonator enhanced Raman spectroscopy. The results are presented in Fig. 10 (c). During our experiment, a $2\text{-}\mu\text{m}$ PS sphere was adhered to the fiber taper. Coupled pump power in the fiber was maintained at 2.75 mW and the micro-Raman collection setup remained the same for each of the measurements. The Raman spectrum obtained without the fiber ring resonator is given by the red curve. The blue curve shows the Raman spectrum measured with the fiber ring resonator, but in this case the frequency of the laser was constantly scanned rather than locked to demonstrate the difference between scanning and cavity locking. Finally, the laser frequency was locked to match a resonant frequency and the measured Raman spectrum of the adhered PS microsphere is plotted by the black curve. The comparison shows that approximately a 1.4 to 1 enhancement ratio is achieved in signal over the background for the PS 3050 cm^{-1} Raman peak, and the collected scattered intensity of the laser indicates a similar enhancement ratio. While these results indicate albeit a modest enhancement factor in our proof-of-concept study, significant room exists for improving the enhancement factor by improving the finesse of the ring resonator or by using other high-Q resonators such as the WGM based fiber resonators.

B.5. Optical Emission Spectroscopy System (Aim 1)

We have shown that the presence of Ni and Cr in welding fumes can be confirmed through optical emission spectrum measurements. The measurement is based on the optical emission spectroscopy system already developed in year 2 of the project period. The schematic of our experimental system is shown in Fig. 11(a).

We measured emission spectra associated with two welding fume samples, with results shown in Fig. 11(b) and 11(c), respectively. Fume sample #1 was produced using an iron base plate and E6011 arc rod with very little Cr and Ni. Fume sample #2 was produced using a stainless base plate and 308LMR arc rod, which contain 20% Cr and 10% Ni. The emission spectra in (b) and (c) clearly show different spectral peaks, with sample #2 containing strong Cr and Ni lines, whereas the corresponding emission lines are much weaker in the spectra associated with sample #1. We have performed ESEM analysis of welding fume sample #1 and #2. As expected, we found significant amounts of Cr and Ni in welding aerosol sample #2, but not in #1.

This study successfully confirms that it is possible to use the optical emission spectra to identify the presence of Ni and Cr in welding fumes generated by the arc welding process.

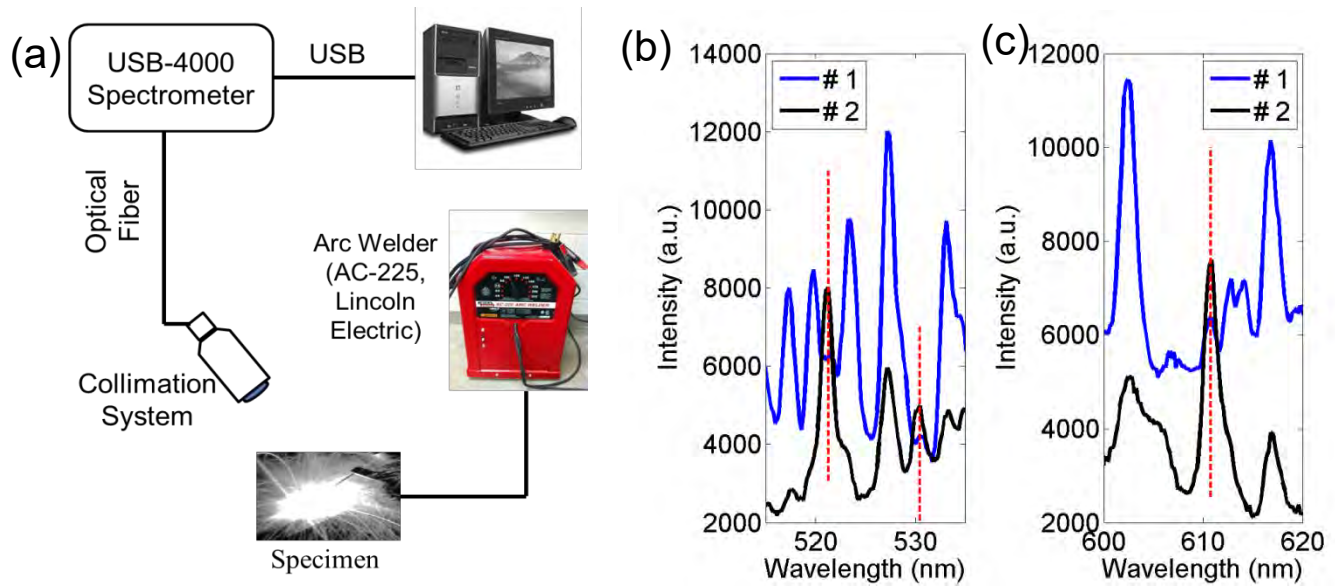


Fig. 11. (a) Schematic of the optical emission spectroscopy system. (b) and (c) show the emission spectra obtained using the system in (a). The blue and black lines in (b) and (c) were measured for two different welding fume samples, #1 and #2. The dashed lines in (b) indicate Cr emission lines at 521.3 nm and 530.5 nm. The dashed line in (c) corresponds to the Ni emission line at 610.8 nm.

B.6 Discussion and Conclusion

The most important result we obtained thus far is Fig. 7, which shows a unique relationship between the measured WGM resonance shift and the amount of welding aerosols deposited onto the resonator surface. Notice that according to our data, even if only 2% of the resonator surface is covered by the welding aerosols, we should be able to detect their presence by monitoring the shift in WGM resonance. Due to the high sensitivity of our WGM-based approach, we cannot even use the conventional method (based on microbalance weighing) to quantify the weight of aerosols collected onto the resonator surface. That is the reason why we have to use aerosol density (A.D.) (instead of using the more conventional measure, which is total aerosol weight) to measure the amount of aerosol deposition.

We can estimate the total weight of the welding aerosols needed to produce a measurable shift in WGM resonance. Note that according to Fig. 6(e), the average diameter of the welding aerosols can be estimated to be 100 nm. Along the axial direction, the range of the WGM should be less than 1 mm. The diameter of the fiber resonator is 0.125 mm. Therefore, for 2% surface coverage, the total volume of welding aerosols within the region of the WGM can be estimated as $4 \times 10^{-7} \text{ mm}^3$. Assuming the aerosol density is approximately 8 g/cm^3 , we find that total aerosol weight is approximately 3 ng. In contrast, most microbalance can only measure weight as small as 1 μg to 0.1 μg . Therefore, we can conclude that the silica-fiber-based WGM sensor, which relies on optical scattering for aerosol sensing, is approximately 100 to 1000 times more sensitive than existing approaches.

Due to the high sensitivity of the fiber-based aerosol sensor, we do not need to pump air across any filter or cascade impactor for aerosol collection. Instead, we let the aerosols to naturally drift towards the sensor and be adsorbed onto the sensor surface. Thus, it is clear that our fiber-based approach is capable of aerosol measurement without no or very little disruption. In other words, we do not need to introduce “artificial” air flow for aerosol measurements. Therefore, our fiber-based approach can perhaps more accurately reflect aerosol distributions in a construction site. Somewhat surprisingly, we find that the aerosols deposited onto the sensor surface are dominated by nanoscale particles. Our finding suggests that it is important to explore the presence of nanoscale aerosols in construction sites, and investigate whether they pose a particular significant health hazard to construction workers.

We point out that we have established the feasibility and operation principles of using WGMs for welding aerosol sensing. The same principle can be applied to other types of aerosols.

In addition to the silica-fiber-based WGM sensor, we have also demonstrated two Raman spectroscopy systems and successfully used them to characterize the presence of micron scale particles. We have also constructed an optical emission system and demonstrated that it is possible to use the emission spectra to identify the presence of harmful elements such as Ni and Cr in welding fumes.

B.7. Publications

Journal Articles

- 1) Yi J, Jao CY, Kandas ILN, Liu B, Xu Y, Robinson HD: [2012] Irreversible adsorption of gold nanospheres on fiber optical tapers and microspheres. *Applied Physics Letters*. 100 (15), Art. No. 153107.
- 2) Kandas I, Zhang B, Daengngam C, Ashry I, Jao CY, Peng B, Ozdemir SK, Robinson HD, Heflin JR, Yang L, Xu Y: [2013] High quality factor silica microspheres functionalized with self-assembled nanomaterials. *Optics Express* 21 (18), 20601-20610.
- 3) Edwards P, Janisch C, Peng B, Zhu J, Ozdemir S, Yang L, and Liu Z: [2014] Label-free particle sensing by fiber taper based Raman spectroscopy. *IEEE Photonics Technology Letters* 26, 2093-2096.
- 4) Lee A, Mills T, and Xu Y: [2015] Nanoscale welding aerosol sensing based on whispering gallery modes in a cylindrical resonator. *Optics Express* 23(6):7351-65.

Proceedings

- 5) Jao CY, Yi J, Kandas ILN, Liu B, Xu Y, Robinson HD: [2012] Absorption of nanoparticles onto curved surfaces. American Physical Society March Meeting 2012, Boston, Massachusetts, February 27-March 2.

Note: Publications 1), 2) and 5) are based on aim 2 of the proposed project. Their purpose is to establish a gold nanoparticle based phantom system for sensor calibration. The main advantage is that by using the phantom system, we can precisely control the amount of nanoparticles adsorbed onto the sensor surface. Publication 3) summarizes our Raman spectroscopy system developed for aim 3. Publication 4) is still under preparation, and will be submitted to Optics Express in November. The results in Publication 4) summarize the performance of silica-fiber-based WGM sensor for welding aerosol detection, developed to address aim 2.

**Project ID 647 - Micro-Processes of Latino Construction Worker Safety:
Feasibility of Computer-Assisted Telephone Surveys**

U60 OH009761

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Abbreviations

BLS	Bureau of Labor Statistics
CATS	Computer Assisted Telephone Survey
CES-D	Center for Epidemiological Studies-Depression
CPWR	Center for Construction Research and Training
DASH	Disabilities of the Arm, Shoulder, and Hand
DPD	Daily process designs
FTE	Full-time equivalent
HOLA	Non-profit organization serving Latino communities of Wilkes and surrounding counties in NC
IVR	Interactive voice response
JCQ	Job Content Questionnaire
OSHA	Occupational Safety and Health Administration
NORA	National-Occupational Research Agenda
PPE	Personal protective equipment
RDQ	Roland-Morris Disability Questionnaire
SD	Standard deviation
XML	Extensible Markup Language

Abstract

Project Title: Micro-Processes of Latino Construction Worker Safety: Feasibility of Computer-Assisted Telephone Surveys

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The goal of this exploratory/developmental project was to determine the feasibility of using daily-process designs with electronic data collection to better understand the role of occupational stress in work-related injury and illness among immigrant Latino workers. We achieved this goal by recruiting a representative but nonrandom sample of 119 immigrant Latino workers in the residential construction industry. Participants participated in up to four distinct data collection elements, including an interviewer-administered baseline survey (N=119), a 21 day end-of-day diary study using computer-assisted telephone survey (CATS) technology (n=90), a debriefing interview following the diary period (n=90), and a 3 month follow-up interview (n=107). Collected data were used to accomplish three specific aims, we: (1) documented participation rates, attrition levels, and adherence to a 21-day end-of-day daily diary protocol using computer assisted telephone surveys (CATS), and loss to follow-up over 3 months of immigrant workers; (2) determined the quality of data collected from the daily process design; and (3) identified design features that could be modified to improve feasibility of daily process designs with immigrant Latinos.

The key findings of this project are:

- 1) CATS technology makes diary studies with Latino samples feasible. Results indicated that over one-third (37%) of the sample adhered to the 21-day end-of-day protocol, a comparable percentage (38.7%) initiated but did not adhere to the protocol, and 24% never began the diary protocol. Adherence was generally not predicted by demographic, health or job-related characteristics.
- 2) Collected data were of sufficient quality to provide a foundation for three published peer-reviewed papers. Most relevant to this aim, results showed that work safety climate measured at baseline predicted safety behaviors reported during the subsequent diary period. These results provide compelling evidence that important safety behavior can be reliably captured with CATS technology.
- 3) CATS technology can be refined to improve the feasibility of daily process designs with immigrant Latinos and the quality of collected data. A key area of refinement discovered was the quality of the computerized "voice": it was reported by participants to sound artificial and as though it had an echo. This and other identified issues have been refined and are currently being used in our follow up project.

Section 1: Executive Summary

Significant (Key) Findings

This project had three aims: 1) documenting Latino construction workers' participation rates, attrition levels, and adherence to a 21-day end-of-day daily diary protocol using a completely automated telephone surveys (CATS), and loss to follow-up over 3 months of immigrant workers; 2) determining the quality of data collected from a daily process study design; and 3) identifying modifiable design features to improve feasibility of daily process study designs with immigrant Latinos. Each of these is discussed in turn.

- 1) CATS technology makes diary studies with Latino samples feasible. Our published results (Grzywacz et al. 2013) indicated that over one-third (37%) of the recruited sample adhered to the 21-day protocol, a comparable percentage (38.7%) initiated but did not adhere to the protocol, and 24% never began the diary protocol. Adherence was generally not predicted by demographic, health or job-related characteristics suggesting few sources of systematic bias in adherence.
- 2) Collected data were of sufficient quality to provide a foundation for three published peer-reviewed papers, in addition to the publication documenting the feasibility of using CATS with Latino workers.
 - I. Most relevant to this aim is a manuscript that combined data from the baseline interviewer-administered survey question with data obtained via CATS. The paper describes work safety climate among Latino residential construction workers, delineates differences in work safety climate by personal and employment characteristics, and determines associations of work safety climate with specific work safety behaviors (Arcury et al. 2012). Key measures included the Perceived Safety Climate Scale, and daily reports of six individual and five collective safety practices. Work safety climate was mixed among workers, with roofers (M=19.9) having lower levels than framers (M=24.3) or general construction workers (M=24.3). Days reported for several individual (glove-related risks, not doing something known to be unsafe) and collective safety practices (attended daily safety meeting, not needing to use damaged equipment, not seeing coworker create an unsafe situation) were positively associated with work safety climate. Work safety climate predicts subsequent safety behaviors among Latino residential construction workers, with differences by trade being particularly important.
 - II. Two additional analyses focused on data obtained through other components of the project. The first analysis sought to determine the potential health threat of work organization to immigrant Latino workers in selected trades in the residential construction industry using longitudinal data from a community-based sample (N=107) (Grzywacz et al. 2012a). 28 participants reported one or more work-related injuries during the 3 month observation period, resulting in an injury incidence rate of 52.8 per 100 FTE. Two injuries involved two or more days away from work, resulting in an incidence rate of 3.8 injuries involving days away from work per 100 FTE. Injuries were elevated among roofers relative to framers and general construction workers. In terms of work organization, variety and control were lowest among roofers and highest among general construction workers, and roofers reported the greatest exposure to occupational hazards. Roofers also reported the lowest levels of supervisory influence over aspects of employment (both negative and positive), and their perceived safety climate was the poorest.
 - III. The second analysis used cross-sectional data from a community-based sample of Latino construction workers in Western North Carolina (N=119) to: describe receipt of employer provided PPE by construction workers, document sources of variation in the receipt of employer-paid PPE, and delineate associations of employer-paid PPE with workers regular use of PPE (Grzywacz et al. 2012b). The results suggest substantial deviation in residential construction subsector from regulations requiring employers to

provide workers with PPE at no cost. Analyses also suggest recent immigrants are most at risk for not receiving no-cost, employer provided PPE, and that employer-provision of no-cost PPE may promote more regular use by Latino construction workers.

- 3) Results obtained from this exploratory/developmental project provided concrete recommendations for refining future implementations of CATS technology with immigrant Latino workers. A key area of refinement discovered was the quality of the computerized “voice”: it was reported by participants to sound artificial and as though it had an echo. We learned this could be addressed by using special features of the program (specifically UTF-8 Unicode as opposed to US ANSI standard character encoding) to better exploit characters, such as the Spanish accents and the tilde, to produce more authentic sounds. We also learned other programming options to help the system differentiate participants’ voices from ambient background noise over the telephone. These refinements have been incorporated into our current project using CATS technology to evaluate a Lay Health Advisor safety training program among Latino roofers.

Translation of Findings

The key finding of this exploratory/developmental project, that CATS technology makes daily process study designs feasible with immigrant Latino workers, does not have direct application to the workplace. However, it provides a powerful tool for future research on occupational safety and health.

Study results reported in the empirical papers have direct implications for preventing workplace injuries. Findings from our paper focused on the work safety climate (Arcury et al., 2012) suggest that active steps to improve the safety climate within small-scale residential construction operations will improve safety behaviors among Latino workers. Specific tactics for improving safety climate will likely differ across construction trades, but all will need to incorporate culturally-competent safety training (to equip workers to engage in safe work practices), greater enforcement of existing regulations and perhaps tax incentives (to incentivize employers to more strongly engage in safety training), and the creation of training modules and other communication strategies (e.g., social norms marketing) targeting supervisors/crew leaders highlighting the importance of subtle behaviors and attitudes pertaining to safety in fostering employees’ safe work practices.

Results from our paper focused on personal protective equipment (PPE) (Grzywacz et al., 2012b) suggest improvements in employers’ adherence to provide no-cost basic PPE would result in greater use of PPE. Advocated strategies to improve employers’ adherence were: 1) greater enforcement of existing statutes, which would be made possible through the creation of a contractor registration system that used common criterion across all states, and 2) the creation of tax credits for the provision of PPE to employees to incentive small-scale contractors who frequently have thin profit margins to provide PPE.

Outcomes/Impact

The results of this exploratory/development project do not have any intermediate or end outcomes for worker safety and health. However, the results have substantial potential to improve worker safety and health. The potential lies primarily in the ability of future research using CATS technology to: 1) identify new risk factors for occupational health, and 2) evaluate interventions to change workers’ safety behavior. These, in turn, will likely create new best practices for promoting safety and health among immigrant Latino workers employed in the small-scale residential construction industry.

Section 2. Scientific Report

Project Background

Work organization and occupational health. The organization of work refers to organizational practices related to management and production methods as well as the way jobs are designed and performed (Sauter et al., 2002). Virtually every element of workers' lives on the job, ranging from the safety climate within the organization to the physical and psychological demands of the work, is shaped by the organization of work. Following 10 years of systematic research initiated by the NORA, substantial evidence indicates that how work is organized contributes to worker health outcomes including adherence to advocated occupational safety behaviors, and onset of musculoskeletal problems, greater risk of compensable spinal injury, experiencing an occupational injury (Kivimaki et al., 2002)(Kuper & Marmot, 2003; Krause, Ragland, Fisher, & Syme, 1998; Swaen, van Amelsvoort, Bultmann, Slangen, & Kant, 2004). Indeed, the organization of work literature provides the backbone of specific goal 9.0 (i.e., Improve the effectiveness of safety and health management programs in construction) of the Construction Sector NORA.

Stress plays a central role in organization of work research. Major models used in the occupational stress literature are based on the premise that job design and the management practices that underlie and reinforce how jobs are designed create stress among workers. The demands-control model (Karasek & Theorell, 1990), for example, argues that jobs that are designed in ways that minimize workers ability to engage in decision making on the job and those that expose workers to excessive demands contribute to poor health. There are two sources of job demands. Physical demands emanate from job-related tasks such as working in awkward postures, having to carry heavy loads, or being exposed to extreme temperatures or dangerous working conditions. Psychological demands emanate from appraisals of physical and social features of the work and the work environment, including subordinate-supervisor relations, the pace of work, and commitment to worker safety.

Little occupational stress research has been done with Latinos, despite the fact they are the fastest growing segment of the labor force (Toossi, 2002), and frequently find themselves in the most dangerous occupations (Mosisa, 2002) and experience a disproportionate share of fatalities and traumatic injuries. Researchers have demonstrated how stressors inherent in migrant farmwork are associated with greater depression, anxiety, and suicidality (Grzywacz et al., 2006; Hiott et al., 2008; Hovey, 2000; Hovey & Magaña, 2002; Magaña & Hovey, 2003). Other research has documented associations between specific stressors, like discrimination and job insecurity, and health-related outcomes (Finch et al., 2000, 2003). These studies suggest that occupational stress threatens the health of Latino workers, but more research is needed, particularly in occupational sectors like manufacturing and construction that employ a disproportionate number of immigrants (Pew Hispanic Center, 2006) and that experience high rates of occupational illness and injury.

Organization of Construction Work. Construction provides a valuable model for studying how the organization of work influences worker health with possible cross-sector generalizability. Construction workers have some of the highest occupational injury rates of all U.S. industries. Construction has the highest number of fatalities of any US industry, over 1200 per year, and in 2007 had over 135,000 nonfatal recordable occupational injuries and illnesses with an incident rate of 5.4, second highest among all US industries(BLS, 2007a). Further, the illness and injury rates reported in the construction industry are likely vast underestimates (Azaroff et al., 2002), especially in the segment

represented by non-fatal, immigrant incidents. Workers view hazards as part of the job, or they move on to other jobs as symptoms develop, especially if they limit work activity (Human Rights Watch, 2004; Lipscomb et al., 2005). Occupational Safety and Health Administration (OSHA) reports, the only source of health statistics for the industry, do not count symptoms or illnesses that are considered by the worker or supervisor to be work-related (Azaroff et al., 2002).

The organization of construction work creates a variety of threats to worker health by undermining safety, including worker safety behavior. Construction, particularly residential construction, operates on small margins resulting in a tendency for operators to operate in a “low bid” mindset. This low bid mentality creates the potential for a variety of circumstances that undermine safe workplace behavior. In smaller firms, where incidents are by far the highest, personal protection equipment (PPE) such as hardhats, safety glasses, reflective vests, respirator, gloves, and hearing protection is typically not provided for workers, and workers are reluctant to pay for these items themselves (McVittie et al., 1997; Ruben et al., 2008). Equipment that is supplied by the contractor and used by workers, such as ladders, hoists, scaffold, and power tools are frequently improper for the job or poorly maintained tools. Heavy reliance on work plans that are delivered orally to workers creates safety problems. Seldom do contractors use a written work plan to execute construction projects. Rather, contractors or crew chiefs issue instructions orally (e.g., ‘...get the ladder and carry these shingles onto the roof’). These types of instructions make strong assumptions about the knowledge, skills, and safety awareness of workers, particularly when workers are non-English speaking and are often perceived as productivity is more important than safety. Commonly observations on construction sites include workers attempting to complete work with improper tools or equipment, doing work without being trained in a specific task, working long hours resulting from rework or poor work task management, and working with defective or inappropriate PPE; all of which result in unsafe conditions and unsafe behaviors.

The nature of construction also produces situations prone to unsafe conditions and worker behaviors. Project delays due to uncontrollable circumstances, such as weather, can result in extended work shifts that leave workers physically exhausted and mentally fatigued. Similarly, priorities to close out work on time or ahead of schedule can lead to short-cuts in enforcements of safety management on the worksite, as well as poor compliance on the part of workers. These, along with the general culture of toughness in the construction industry as well as the physical environment pose systemic threats to worker health and safety.

Construction workers are increasingly ethnic minority, and foreign born. For instance, during 1995 and 1996 Hispanics represented 10% of all workers in the construction industry; in 2001 the percentage reached 18% or 1.3 million, and in 2007 it reached 30% or 2.85 million. This represents an increase of more than 300% for the last 12 years (Brunette, 2004). The safe management of this workforce is clearly a challenge to all construction professionals, as indicated by a recent report by the Associated General Contractors of America (2008, p. 1) stating, “nearly ¼ of current construction workforce is Hispanic ... and the number is expected to increase. Latino immigrants are often illegal, illiterate and do not speak English.” These workers also populate some of the more dangerous trades in the most dangerous sectors including agriculture.

The burden of injury and illness among roofers and framers. The impact of injury and illness by roofers and framers in days away from work, job transfer, or work restriction is much higher than the industry as a whole with roofers at 40% higher and framers at 75% higher (BLS, 2007b). These are clearly high risk occupations. Framing contractors have a higher overall injury and illness incident rate than roofing contractors 8.1 to 6.5/100 full time workers yet both exceed the overall construction sector incident rate of 5.4. Framers have a work related injuries rate twice the national

average and are considered a 'high risk' occupation. This is a result of the fact that framers frequently are working with heavy wood materials that often result in injuries such as overexertion, and strains due to improper lifting techniques and straining with work that is placed above their heads and power tools that result in cuts, lacerations, and finger amputations. Additionally cuts, scrapes, splinters, bruising, and carpal tunnel syndrome are often common. Due to the nature of the work, nail gun related injuries and being struck by other materials are other injuries characteristic to framers (BLS, 2007b).

Roofers on the other hand appear more prone to work related illness a rate 2.5 times that of framers as evidenced by a significantly higher incident of skin disorders and breathing related issues. The most frequently cited roofer injuries are a result of falls, struck by, and overexertion mainly caused by frequently lifting materials weighing 50 pounds or greater. Overexertion results in roofers having a larger number of strains, sprains, and back injuries than other workers but at a rate slightly lower than framers. These injuries are followed in frequency by fractures and cuts (Fredricks et al., 2005).

Roofers and framers in residential construction are particularly at risk for injury and illness. Due to the nature of the work and heavy lobbying by the residential construction industry, fall protection in residential construction is governed under a modification to OSHA 1926. Std.3-0.1A modifies OSHA fall protection requirements specifically for residential construction work by allowing minimal level alternative safety procedures (see

http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=DIRECTIVES&p_id=2288).

According to the modification no showing of infeasibility of conventional fall protection is needed before using these procedures. A fall protection plan is required but it does not have to be written nor does it have to be specific to the jobsite. Different alternative procedures are specified for different activities and these alternative procedures are less stringent than the standard fall protection requirements. Coupled with these alternative procedures is the 2007 statistic that there were 93 fatalities caused by falls in residential building construction to 86 for non residential construction, an 8% higher fatality rate, while in 2006 there were 120 fatalities due to falls in residential construction trades to 60 fall related fatalities in the non-residential building construction trades or 200% greater. (BLS, 2006, 2007)

Daily process study designs. DPDs capture the experiences of individuals' lives as they are lived. As Bolger and colleagues (2003) summarized, "DPDs permit the examination of reported events and experiences in their natural, spontaneous context, providing information complementary to that obtainable by more traditional designs" (p. 580). One of the major points underlying DPDs is that individuals' lives are subject to substantial day-to-day variation in a host of experiences, like stress exposure as well as affective and behavioral responses to stress (Tennen et al., 2000). This "within-person" variation has potentially significant implications for understanding patterns of human behavior and health (Burton et al., 2007; Grzywacz et al., 2004), yet within-person variation is lost in most nomothetic study designs frequently used in occupational health and safety research like cross-sectional surveys (Tennen et al., 2000; Stone & Shiffman, 2002). Case-crossover designs are valuable for capturing the potential effect of transient work-related conditions on acute events such as serious injury (Checkoway et al., 2007). However, case-crossover studies are not well-suited for studying behavior and the role that environmental circumstances such as occupational stress play in promoting or undermining advocated safety practices among workers (Checkoway et al., 2007).

Apart from capturing within-person variation in key experiences pertinent to human behavior and health, DPDs have several notable strengths. First, reporting biases are minimized because there is a narrower time between when an individual experiences an event and when that event is reported (Tennen et al., 2000). Next, several features of DPDs allow for strong causal inference. They capture the temporal sequence of events and experiences so that researchers can more firmly establish the

temporal relationship between putative antecedents, like stress exposure, and consequences (e.g., symptoms). More importantly, analyses of data from DPDs allow for individuals to serve as their own control because outcomes, like symptoms, can be compared on days with and without the presumed cause of symptom activation (e.g., stress exposure). This type of analysis provides a strong test of a causal relationship.

Given their many strengths, DPDs are increasingly applied in occupational health research. Early research, for example, documented how variation in exposure to occupational stressors in natural environments was associated with variation in heart rate and blood pressure (Theorell et al., 1988; Shapiro et al., 1993). More recently, DPDs have been used to study risk factors for occupational injury (McNamara & Bagramian, 1999), the role of daily indicators of job strain in hypertension (Tobe et al., 2005) and cardiovascular disease risk (Collins et al., 2005), as well as the effectiveness of ergonomics interventions in the workplace (Ketola et al., 2002). The application of DPDs designs in immigrant worker populations is notably absent from this literature.

Although there are several strengths to DPDs, there are also noteworthy challenges (Bolger et al., 2003). DPDs, including end of day diary studies, are demanding on participants because of frequent reporting over extended periods of time. The reporting burden may be exacerbated when electronic data collection systems are used and participants are unaccustomed to using electronic devices (Palmlad & Tiplady, 2004). There is a general concern that repeated reporting of daily events and circumstances may affect reporting patterns, such that individuals may either become more attuned to measured events or circumstances which may inflate responses, or they may become habituated to the diary and give incomplete attention to questions. Although widely raised, the actual threat of these concerns to the validity of diary studies awaits further research (Bolger et al., 2003; Stone & Shiffman, 2002). Several of these issues are particularly challenging when conducting research with immigrant Latinos. Generally low levels of education among Latinos raise concerns about participants' ability to read, understand and respond to diary questions. The burden of a diary studies may be elevated among immigrant Latinos who are unaccustomed to participating in research, and who may be intimidated by electronic devices used in data collection. Economic challenges confronted by immigrants pose another challenge because participants may misuse (or sell) data collection devices for personal need (Clark & Zimmer, 2001). Contextual factors ranging from concerns about documentation and possible deportation to inadequate housing raise several potential barriers to enrolling and remaining compliant with the more intensive data collection protocol required by daily process designs. All of these issues need to be overcome to capture the potential benefit of DPDs for understanding ethnic disparities in health and the extent to which occupational circumstances contribute to health disparities.

Summary. There is substantial interest in understanding how the organization of work and occupational stress contributes to advocated safety behavior and worker health. Yet, despite widespread interest there has been very little organization of work and occupational stress research performed with immigrant Latinos, the fastest growing segment of the U.S. workforce and a population that is disproportionately represented in dangerous occupations and in fatality and injury statistics. DPDs, such as those that collect diary data at the end of each day using electronic devices, have substantial potential for occupational safety and health research, but they are not widely used. There have been no studies using DPDs with immigrant Latinos. There are significant challenges to implementing DPDs with immigrant Latinos, including issues pertaining to literacy, familiarity with electronic devices used in data collection, and maintaining compliance with an intensive, daily data collection protocol. Overcoming these barriers is crucial to ensuring that understanding of immigrant

health is not stymied by over-reliance on less sophisticated study designs (Bolger et al., 2003). Overcoming the challenges of DPDs with immigrants will also open new doors for understanding the role of occupational stressors in immigrant worker health and for designing workplace safety interventions to reduce occupational health disparities.

Project Specific Aims

Construction workers' adherence to advocated safety behavior is likely shaped by day-to-day variation in job-related stressors. Excessive job demands stimulate "short cuts" that threaten safety, likewise preoccupation or distraction from job stress likely interferes with safe practices. The goal of this exploratory/developmental project is to determine the feasibility of using daily process designs (DPD) with electronic data capture to better understand the role of occupational stress in safety behavior and work-related injury among immigrant Latino construction workers. Daily process designs document patterns of events and behavior within individuals as opposed to between individuals (Bolger et al., 2003; Tennen et al., 2000), and are characterized by multiple brief assessments (e.g., diaries) over a discrete time period. Electronic data capture such as automated telephone surveys are increasingly used because paper and pencil systems are inferior (Stone et al., 2003).

DPDs with electronic data capture offer strong promise for understanding health and health disparities (Grzywacz et al., 2004). DPD reduce potential for reporting error and improve measurement sensitivity by condensing the period between experiencing and reporting an event (Affleck et al., 1999; Tennen et al., 2000). This feature is invaluable for documenting the incidence and prevalence of minor, frequently unreported injuries and the circumstances surrounding injury. DPD allow clear temporal sequencing of events (e.g., stress exposure) and outcome (e.g., behavior). This feature has clear advantages for understanding behavior patterns that increase injury risk, such as adherence to advocated safety practices. Finally, DPDs allow individuals to serve as their own control. Allowing individuals to serve as their own control coupled with a clear temporal sequence and strong theory improve the ability to make causal inferences with non-experimental data. DPDs provide a powerful tool for linking occupational stress exposure to worker safety behaviors and subsequent health, thereby providing needed information for creating effective safety interventions.

There are several challenges to implementing DPDs with electronic data capture, particularly in hard-to-reach populations like immigrant Latinos. Diaries require basic reading and writing skills: a challenging requirement for immigrant Latinos who may have limited literacy. Unfamiliarity with technology, particularly handheld technology, could undermine compliance or influence (bias) responses to questions (Palmlblad & Tiplady, 2004). Economic challenges confronted by immigrants pose another problem because participants may misuse data collection devices for personal need (Clark & Zimmer, 2001).

Immigrant Latino construction workers are the focus of this project. Construction is stressful, physically demanding, and dangerous work, and Latinos are over-represented in the construction workforce. Fully 25% of construction workers are Latino (BLS, 2008), including 2.1 million foreign born workers, one-third of whom are undocumented (Pew Hispanic Center, 2009). Many of these workers are in the lightly regulated residential construction industry. The fact that Latinos are over-represented in residential construction, and that construction is stressful and dangerous work make it an ideal context for studying the feasibility of using DPDs to study how occupational stress affects safety behavior and potential injury among immigrant laborers.

The goal of this exploratory/developmental project will be achieved by accomplishing three specific aims.

Specific Aim #1: Document Latino construction workers' participation rates, attrition levels, and adherence to a

21-day end-of-day daily diary protocol using a completely automated telephone surveys (CATS), and loss to follow-up over 3 months of immigrant workers.

Specific Aim #2: Determine the quality of data collected from the DPD.

Specific Aim #3: Identify modifiable design features to improve feasibility of DPDs with immigrant Latinos.

Within the NORA Construction Sector, this proposed research focuses primarily on Construction Safety and Health (Strategic Goal 9.0), but it also addresses work organization (Strategic Goal 10.0) and stress-related disorders such as work-related musculoskeletal disorders (WMSDs) (Research Goal 7.3.3), as well as Occupational Health Disparities (Strategic Goal 12.0). Beyond the specific focus on construction workers, this project is one of the first applications of the daily process design to study occupational stress and health outcomes in an immigrant population. If feasibility is established, this project will open new paths for occupational health research including the study of factors contributing to the onset and progression of occupational illnesses, compliance with safety standards, documenting the frequency of minor or other unreported injuries, or evaluating the effectiveness of interventions designed to promote safe workplace practices. Each of these is valuable for workers in general, and specifically for minority and immigrant workers who are over-represented in dangerous occupations.

Project Method

Sample. Participants were a non-probability sample (N=119) of residential construction workers who self-identified as Latino. Participants were recruited in partnership with HOLA (Hogar Latino) of Wilkes County. HOLA is a 501(c)(3) non-profit organization that serves the Latino communities of Wilkes and surrounding counties in western NC, a region of the country characterized as a “new settlement community” because of the sharp increase in Latino population since 1990 (Kochhar et al., 2005). A main emphasis of HOLA's mission is to empower the Latino community to improve their health through the promotion of education and by strengthening understanding and cooperation between Latinos and the broader community. HOLA staff recruited residential construction workers through a combination of techniques including through known constructions workers in existing social networks, snowball sampling or identification of individuals who may be study eligible by existing participants, and referral (identification of individuals who may be study eligible by non-participants). Study inclusion criterion were age 18 years or older, Latino (self or parents born in a Latin American country, or self-identified as “Latino” or “Hispanic”), and employment for 35 or more hours per week in construction. There were no exclusion criteria. A federally authorized Institutional Review Board (FWA #00001435) approved all sampling, recruitment and data collection procedures.

The study design called for workers in each of three construction trades: framing, roofing, and general labor. Individuals were classified as being a framer if they were usually involved in building or assembling floors, walls, or roofs using lumber or light gauge metal framing at least three days per week. Participants were classified as roofers if they were usually involved in applying roof shingles, removing existing roof shingles, applying hot roofing tar or built up roofing, or carrying roofing materials onto a roof at least 3 days per week. Individuals who self identified as being a general construction worker and did not meet the definition of “framer” or “roofer” were classified as being a general construction worker.

Data Collection. The project included 4 distinct data collection elements. The first data collection element was a baseline interviewer-administered interview, which assessed stable attributes of the individual (e.g., age, country of origin), occupational characteristics (e.g., years in construction, primary tasks performed in construction), and a health history (e.g., presence of chronic conditions). These data were collected by four trained interviewers, all of whom were native Spanish-speakers. Interviewer training consisted of a thorough review of study purpose, screening and recruitment procedures, line-by-line review of the interviewer-administered questionnaires, and progressively more realistic practice interviews. The baseline interview was completed by N=119 participants and took an average of 48.1 (SD = 62.0) minutes to complete. Participants received a \$15 incentive.

The second data collection element was a 21-day daily diary implemented using IVR technology (PlumVoice, Cambridge MA). The 21-day period was selected based on practical considerations; specifically, we wanted to capture at least two weeks of work-day observations while accommodating likely fluidity in work schedules (e.g., missed work because of inclement weather). The IVR data collection system was designed and built using VoiceXML. The VoiceXML program guided participants through a series of questions about daily health symptoms, and a variety of work-related experiences and exposures. The VoiceXML was programmed to follow a selection logic dependent on the type of work done on each day. This logic provided flexibility such that individuals who did not work on a given day were not asked work-related questions, while other questions relevant to specific tasks (e.g., ladder safety) could be skipped if deemed irrelevant (e.g., reported not using a ladder during that work day). Participants received up to \$73 for completing the 21-day daily diary protocol, which essentially translates into \$3 per call plus \$10 to cover cell phone minutes that may have been used to participate in the study.

The third data collection element was a short debriefing interview implemented by trained, native Spanish-speaking interviewer. The debriefing interview consisted of structured questions about participants' experiences with the IVR technology, as well as open-ended questions probing for detail when needed. This analysis draws on responses to the structured questions.

The fourth data collection element was a interviewer-administered survey questionnaire that was completed 3 months after the baseline interview. The content of the follow-up interview focused primarily on experiences of injury and changes in health during the preceding 3-month period. The follow-up interview took 24 min, on average, to complete, and participants received a \$25 incentive.

All participants provided signed informed consent before any data were collected. All recruitment and data collection activities were approved by the Wake Forest School of Medicine Institutional Review Board (FWA #00001435).

The content of each data collection element underwent thorough translation and back-translation procedures. Content from validated Spanish instruments (e.g., SF-12 questionnaire for assessing health-related quality of life) were used without modification. English-only instruments and items developed for this project were translated into Spanish by a native Spanish-speaker. All items were then back translated into English by an English-speaker. Discrepancies identified in the back translation were corrected through consensus and incorporated into both the Spanish and English versions of questionnaires.

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Project Results

Paper #1. The Feasibility of Interactive Voice Response Methods in Health Behavior Research with Immigrant Latinos

Paper #1, Background

Study designs that use repeated measures over discrete periods of time, like end-of-day diary studies, offer several strengths for understanding health behaviors.^{1,2} One key benefit is reduced measurement problems because the shorter time between experiencing an event and subsequent reporting of the event.¹ Another benefit of daily diary study designs is that they are able to capture “life as it is lived”.³⁻⁵ The repeated observations over a series of multiple days allows the capture of both highly routinized aspects of daily life and more unusual types of events. Greater capture of the circumstances and experiences of daily life allows for a more complete, and, presumably valid, description of human behavior and are therefore valuable for health research. Further, because observations are captured in a sequence of time, daily diaries enable analytic techniques that allow maximal causal inference from observational data because investigators can capture and model the temporal ordering of observed phenomenon, thereby allowing individuals to essentially serve as their own controls.^{1,3}

Fielding daily diary studies can be challenging in low literacy populations. Collecting diary data is challenging because they typically require participants to be able to read and potentially write, regardless of whether data are captured using paper and pencil or an electronic device (e.g., Personal Digital Assistants, Tablet PC). Literacy issues can be partially remedied by the use of interviewer-administered methods (either in person or by telephone); however, interviewer-administered methods require substantial personnel time, and may not be feasible either because of costs or sensitivity of the topic under study. Even more problematic is the coordination effort that may be needed to ensure that interviewers are available when data are to be collected. Irregular or chaotic daily schedules of study participants can compromise even the best-laid data collection plans.

Interactive voice response (IVR) technology offers substantial promise to health research, particularly research with low literacy populations.⁶ IVR technology uses stored, pre-recorded questions or Voice Extensible Markup Language (VoiceXML) to deliver audible questions to study participants over the telephone. Participants can respond to questions by entering a number as a text response on their telephone’s keypad, or by responding verbally. Although not without costs and limitations, there are many benefits of this technology. The use of a telephone and audio-based data collection system eliminates the need for participants to read or write, and it can accommodate non-English speaking individuals. IVR ensures that all participants receive the same stimulus, thereby minimizing potential interviewer effects. The date and time of each diary entry is electronically stamped allowing rigorous evaluation of adherence to the data collection protocol. Finally, provided they have a telephone, participants can access the data collection system virtually anytime and from anywhere.

IVR technology has been used in research for over 20 years.⁶ IVR has been used most extensively in studies of alcohol use and misuse. Collins and colleagues⁷ documented that IVR technology yielded reliable data from social drinkers, while having several benefits, such as ease of use by participants and date/time stamping of data entries. Midanik and Greenfield⁸ evaluated the use of IVR in the context of the 2005 National Alcohol Survey and reported that IVR was particularly useful for individuals for whom survey content was sensitive. Outside of alcohol research, IVR has been used to study

sexual behavior,^{9,10} mistreatment of elders,¹¹ post-partum depression among low-income mothers,¹² post-discharge adverse events,¹³ and medication adherence.^{14,15} Absent from this growing area of research is any application of the method with low-literacy, non-English speaking individuals. One study did compare the use of IVR in contrast to paper-and-pencil methods of collecting data on symptoms from Spanish-speaking patients, and found that each method yielded similar results.¹⁶

The goal of this study was to develop a better understanding of the potential value of IVR technology in fielding daily diary studies in low literacy populations. In this study the focus was immigrant Latino workers in the residential construction industry. Latino construction workers provide an excellent model for evaluating the feasibility of IVR technology as they typically have modest levels of formal education¹⁷ suggesting limited literacy. The length and time of the workday can be highly variable and heavily influenced by external factors, such as weather-related delays and overall demand for services. Finally, immigrant Latino construction workers experience an elevated burden of occupational injuries, many of which are believed to go unreported either because they are perceived as minor or because workers are reluctant to report the injury to their employer out of fear of reprisal or sanction.¹⁸⁻²⁰

The primary objective of this analysis is to determine the feasibility of using IVR technology to field a daily diary study focused on work-related stressors and safety behavior in the workplace among immigrant Latino residential construction workers. To achieve this objective, this analysis: describes participant adherence to a 21-day end-of-day daily diary protocol using IVR technology; delineates demographic, individual, and work-related sources of non-adherence to the diary protocol; and documents variation in key call attributes (the number and duration of diary entries) and responses to a debriefing interview about the IVR technology by participant adherence status.

Paper #1, Methods and Materials

Sample. Participants were a non-probability sample (N=119) of residential construction workers who self-identified as Latino. Participants were recruited in partnership with HOLA (Hogar Latino) of Wilkes County. HOLA is a 501(c)(3) non-profit organization that serves the Latino communities of Wilkes and surrounding counties in western NC, a region of the country characterized as a “new settlement community” because of the sharp increase in Latino population since 1990 (Kochhar et al., 2005). A main emphasis of HOLA’s mission is to empower the Latino community to improve their health through the promotion of education and by strengthening understanding and cooperation between Latinos and the broader community. HOLA staff recruited residential construction workers through a combination of techniques including through known constructions workers in existing social networks, snowball sampling or identification of individuals who may be study eligible by existing participants, and referral (identification of individuals who may be study eligible by non-participants). Study inclusion criterion were age 18 years or older, Latino (self or parents born in a Latin American country, or self-identified as “Latino” or “Hispanic”), and employment for 35 or more hours per week in construction. There were no exclusion criteria. A federally authorized Institutional Review Board (FWA #00001435) approved all sampling, recruitment and data collection procedures.

The study design called for workers in each of three construction trades: framing, roofing, and general labor. Individuals were classified as being a framer if they were usually involved in building or assembling floors, walls, or roofs using lumber or light gauge metal framing at least three days per week. Participants were classified as roofers if they were usually involved in applying roof shingles, removing existing roof shingles, applying hot roofing tar or built up roofing, or carrying roofing materials onto a roof at least 3 days per week. Individuals who self identified as being a general construction worker and did not meet the definition of “framer” or “roofer” were classified as being a general construction worker.

Data Collection. The data for this analysis come from three elements of the overall project. The first data collection element was a baseline interviewer-administered interview, which assessed stable attributes of the individual (e.g., age, country of origin), occupational characteristics (e.g., years in construction, primary tasks performed in construction), and a health history (e.g., presence of chronic conditions). These data were collected by four trained interviewers, all of whom were native Spanish-speakers. Interviewer training consisted of a thorough review of study purpose, screening and recruitment procedures, line-by-line review of the interviewer-administered questionnaires, and progressively more realistic practice interviews. The baseline interview was completed by N=119 participants and took an average of 48.1 (SD = 62.0) minutes to complete. Participants received a \$15 incentive.

The second data collection element was a 21-day daily diary implemented using IVR technology (PlumVoice, Cambridge MA). The 21-day period was selected based on practical considerations; specifically, we wanted to capture at least two weeks of work-day observations while accommodating likely fluidity in work schedules (e.g., missed work because of inclement weather). The IVR data collection system was designed and built using VoiceXML. The VoiceXML program guided participants through a series of questions about daily health symptoms, and a variety of work-related experiences and exposures. The VoiceXML was programmed to follow a selection logic dependent on the type of work done on each day. This logic provided flexibility such that individuals who did not work on a given day were not asked work-related questions, while other questions relevant to specific tasks (e.g., ladder safety) could be skipped if deemed irrelevant (e.g., reported not using a ladder during that work day). Participants received up to \$73 for completing the 21-day daily diary protocol, which essentially translates into \$3 per call plus \$10 to cover cell phone minutes that may have been used to participate in the study.

The third data collection element was a short debriefing interview implemented by trained, native Spanish-speaking interviewer. The debriefing interview consisted of structured questions about participants' experiences with the IVR technology, as well as open-ended questions probing for detail when needed. This analysis draws on responses to the structured questions.

The content of each data collection element underwent thorough translation and back-translation procedures. Content from validated Spanish instruments (e.g., SF-12 questionnaire for assessing health-related quality of life) were used without modification. English-only instruments and items developed for this project were translated into Spanish by a native Spanish-speaker. All items were then back translated into English by an English-speaker. Discrepancies identified in the back translation were corrected through consensus and incorporated into both the Spanish and English versions of questionnaires.²¹

Measures. Participants were classified into one of three mutually-exclusive groups based upon their number of completed calls during the 21-day diary period. Participants were classified as “non-completers” if they never completed a daily diary using the IVR system. Participants who logged into the IVR system at least once but completed fewer than 85% of the calls (fewer than 18 calls during the 21-day period) were classified as “non-adherent”. “Adherent” participants were those that completed a telephone diary on 85% or more of the call days (i.e., 18 or more calls during the 21-day period).

Demographic characteristics. The baseline questionnaire contained several measures of basic demographic characteristics, by which adherence to the diary protocol might differ. These characteristics included *age* (measured in years), *gender*, *marital status* (single/unmarried, married/living as married with partner in the U.S., and married/living as married with partner in country of origin), *educational attainment* based upon the grading system used in Mexico and other Latin

American countries (i.e., primary education or less, secondary education, and preparatory education or higher), and *length of residence* in the U.S. (≤ 7 years, 8-15 years, ≥ 16 years).

Health. Participants' physical and mental health could influence adherence to the 21-day diary protocol. Health was assessed with four instruments in the baseline questionnaire. The first instrument was the Disabilities of the Arm, Shoulder, and Hand (DASH) questionnaire, developed to measure *impairment and limitations in activities due to disorders of the upper limbs*. The DASH is comprised of 30 items and has been translated and validated in Spanish.²² The second measure, the Roland-Morris Disability Questionnaire (RDQ), is a 24-item instrument designed to measure *physical disability due to low back pain*. The RDQ has been translated into Spanish²³ and is reported to have good internal consistency.²⁴ Third, the Medical Outcomes Short Form-12 Health Survey, V 2.0, Acute form²⁵ was used to assess health-related quality of life; proprietary algorithms were used to construct norms-based scores for physical and mental health (i.e., PCS and MCS). Finally, *Depressive symptoms* were assessed with the Center for Epidemiological Studies-Depression scale (CES-D).²⁶ The CES-D is a widely used instrument, with previous studies demonstrating adequate internal consistency (.81 - .90) and construct validity (.80) in Mexican and Mexican-American samples.²⁷⁻³⁰ The 20 items of the CES-D are summed, with higher values indicating greater depressive symptoms.

Occupational characteristics. Discrete features of participants' jobs may influence their ability to adhere to the diary protocol. Individuals were classified at recruitment based on the inclusion criterion into one of three mutually exclusive categories (i.e., framer, roofer, and general construction). *Hours worked per week* in construction and *weeks worked in construction* in the previous 12 months were reported by participants during the baseline questionnaire.

Several variables reflecting the organization of work were measured in the baseline questionnaire using established instruments. Job design and performance variables were assessed using a modified version of the Job Content Questionnaire (JCQ).³¹ Based on previous research with immigrant Latinos suggesting difficulty responding to affectively based response items (e.g., 'strongly agree' versus 'strongly disagree'),^{32,33} the JCQ was modified to use a 4-point frequency-based response set ('never' to 'always'). *Control* was assessed with 3 items tapping opportunities to exert control over work (e.g., "How often are you allowed to make your own decisions about your work?"). *Variety* was assessed with three items (e.g., "How often do you do a variety of different things on your job?"). *Psychological demand* was assessed with four items tapping the stressors inherent in participants' jobs (e.g., "How often is your job hectic?"). Items for each concept were coded and summed such that higher values indicated greater frequency of exposure to the latent concept. The estimated internal consistency of the control, variety, and psychological demand scales were 0.92, 0.68 and 0.66 respectively.

Perceived safety commitment was assessed using an existing 7-item scale³⁴ and constructed by coding and summing the items so that higher values indicate greater perceived management commitment to worker safety ($\alpha = .74$). *Abusive supervision* was measured with a 7-item index assessing the extent to which supervisors/managers use coercive tactics with their employees.³⁵ Items were summed with higher values indicating greater use coercive tactics by managers/crew chiefs ($\alpha = .75$).

Analysis. The main variable of interest in this analysis is adherence status, which is a discrete categorical variable constructed from the number of days a participant completed a daily diary. Frequencies and percentages were calculated to describe participants in each adherence category. Chi-square tests were used to test for differences among adherence status groups on categorical measures, most of which were demographic characteristics (e.g., age group, marital status, education...). One-way analysis of variance was used to make comparisons in measures of health at

baseline (e.g., DASH, CES-D) among the adherence status groups, and logistic regression models were fit to test for differences between adherence status groups on continuous measures of work characteristics (e.g., hours of work per week, weeks of construction). Statistical tests were considered significant at $p < .05$.

Paper #1, Results

The sample consisted primarily of young men (Table A1). All participants except for 1 were male, and fully one-third were less than 29 years of age and over 75% were less than 39 years. The majority of participants were married, and their spouses were in the US. The modal educational attainment was *Secundaria*, which is generally comparable to a 6th-9th grade education in the US. Over one-third of participants had been in the US for fewer than 7 years and nearly 85% had been in the US for fewer than 15 years. Over three-quarters of the sample was from Mexico, while the remainder were from another country, primarily Honduras or Guatemala.

One-quarter ($n=29$) of the sample was classified as non-completers; these participants did not complete one daily diary using the IVR system. Comparable numbers of participants were classified as non-adherent ($n=46$, 38.7%) and adherent ($n=44$, 37%). The percentage of non-completers was greater in the second half of the recruitment and data collection period than in the first half. Otherwise, there were no demographic differences among non-completers, those that were non-adherent, and those who were adherent.

The average participant received a score of 3.4 ($SD=4.9$) on the Disability of the Arm, Shoulder and Hand instrument, and a score of 0.3 ($SD=1.7$) on the Rolland-Morris instrument assessing back pain (Table A2). Physical health-related quality of life and mental health-related quality of life were both below the population norm-based score of 50. Participants had an average depressive symptoms score of 12.9 ($SD=4.8$). Importantly, none of health characteristics assessed at the baseline interview differed by adherence to the diary protocol.

There was very little evidence that adherence status to the diary protocol systematically differed by work or job characteristics measured at baseline (Table A3). Framers were more likely to be classified as non-completers, while roofers and general construction laborers were more likely to be classified as adherent and non-adherent, respectively. Otherwise, there were no differences in either structural aspects of construction employment (e.g., hours of work/week, weeks in construction) or the way the work is organized (e.g., control, psychological demand, safety climate).

Call behavior was systematically different for adherent participants compared to non-adherent participants, as would be expected given the way adherence was defined. Adherent participants completed, on average, 19 ($SD=2.3$) telephone calls during the 21-day period. The average length of the call during work days was 13.6 minutes ($SD=3.2$ minutes), while the average call length on non-work days was 3.5 minutes ($SD=3.8$). Non-adherent participants completed 9 calls, on average, during the 21-day period, and their calls tended to be approximately one minute shorter than calls completed by adherent participants on both work and non-work days.

During the debriefing interview the vast majority of participants reported that questions asked during the daily diary made sense given the type of work performed, and that the telephone calls were perceived as “easy” (Table A4). Over two-thirds of the sample reported liking the confidentiality of answering work-related questions asked by a computer instead of person. Nearly three-quarters of the sample reported that they would participate in another study using the IVR technology; however, trend-level evidence ($p < 0.10$) suggests that non-adherent participants were less likely to agree with this statement than adherent participants. The debriefing interviews also identified areas requiring consideration and

attention in future research. Nearly two-thirds of the sample reported having problems because the IVR system did not understand or recognize the participant's response to a question, and nearly 40% of participants reported getting cut off and having to restart the interview one or more times. Nearly half of the sample reported difficulty remembering to call each day; this was the only debriefing item that differed significantly between adherent and non-adherent participants. Over 40% of participants reported never becoming comfortable answering questions asked by a computer. Finally, at least one in seven participants reported purposively skipping at least one telephone call because it took too many minutes from their cell phone plan.

Paper #1, Discussion

Daily diary-type studies provide valuable insight for understanding human health behavior, but implementing these types of studies can be challenging in different segments of society.⁶ Literacy and language issues pose significant challenges to collecting high quality data. IVR technology overcomes many of these challenges and it has been used to study various behaviors; however, the feasibility of this method among low literacy Latino immigrants remains understudied. This study addressed this gap and the results make several contributions to the literature.

IVR technology can be used to study health behaviors in samples of immigrant Latinos from Mexico. Our data indicate that over one-third of the sample adhered to the diary protocol using IVR technology, with minimal prompting. Results further indicate that the likelihood of adhering to the protocol do not systematically differ by several demographic, health, and job or occupational characteristics. These results are consistent with previous research supporting the feasibility of IVR technology with non-English speaking Latino individuals,¹⁶ as well as results suggesting that IVR technology is feasible for collecting data from low-income and other hard-to-reach study populations,¹² and for collecting data on sensitive topics (e.g., non-heterosexual orientation among specific groups).⁸ Our results extend this research by indicating that IVR technology can be usefully applied in community-based research with non-English speaking immigrant populations, as well as health behavior research pertaining to occupational safety.

However, future research using IVR technology for data collection with immigrant Latinos should be attentive to three distinct results from this study. First, approximately two-thirds of the study sample did not adhere to the protocol: about 25% never started the diary protocol, and another 38% did not complete at least 85% of the required calls. As researchers advance the use of IVR methods in future studies with immigrant Latinos, attention needs to be given to alternative strategies for promoting adherence to telephone call protocol. Several strategies are advocated to enhance adherence to daily diary-type protocols such as complete training on how to use data collection procedures, using reminder devices, and letting participants know that overall adherence will be monitored and taken into consideration when awarding the study incentive.³ These strategies were not emphasized in this study so that we could better evaluate the feasibility of the method, but the results suggest that strategies such as these may be even more salient in this population. Second, our findings reinforce reports of the perils of paper-and-pencil diaries² and one strength of IVR technology; that is, the ability to rigorously evaluate adherence using the time and date stamp of each diary entry.

Our finding that adherence to the diary protocol differed between the first and second half of the recruitment and data collection period is also useful. We interpret this difference as reflective of the *personalismo* or the strength of the interpersonal relationship of project personnel (i.e., the data collector) with study participants. That is, data collectors recruited individuals within their social networks first, and the personal relationship inherent in these social networks enabled better

adherence. However, as study eligible participants within the data collectors' social networks were exhausted, the implicit obligation among individuals with an established social relationship was likely weakened thereby contributing to poorer adherence. This interpretation is consistent with previous reports of the importance of *personalismo* for recruiting Latinos into research focused on health and related processes,³⁶⁻³⁸ and suggests that future studies involving IVR technology with immigrant Latinos will need to complement existing recruitment and retention tactics with those that build-in and capitalize on *personalismo*.

Results from the debriefing interviews also provide insight into specific ways to enhance future use of IVR technology for field diary studies with immigrant Latinos. An unacceptably high number of individuals experienced difficulties with the IVR system, both in terms of the number of individuals reporting the system did not understand a response or because they were cut off during a session. Future applications need to be attentive to subtle features of the VoiceXML coding to enhance users experience. Two key examples were learned from this project. The first is the importance of hardware and supporting programming that allows differentiation of voice responses from ambient noise. Recognizing that many of these calls took place on a cell phone in the truck on the way home from the job site, the computer needs to differentiate noise from the radio or a rolled down window from actual voice inputs provided by the respondent to asked questions. Second, this experience highlights the importance of subtle technologic and programming logic that affects the sound quality of the VoiceXML application. This is particularly important when speaking Spanish. Once the project was completed we realized that to fully utilize foreign characters such as Spanish accent characters we need to ensure that the VoiceXML was encoded in utf-8 (Unicode) as opposed to the US ANSI standard encoding character set.

The contributions of this study must be considered in light of its limitations. First, the generalizability of study findings is unknown because the sample was small, regional, and recruited using non-probability methods. Next, the field of possible predictors of differential adherence to the diary protocol was circumscribed. Although we considered many useful demographic, individual (i.e., health), and job-related determinants of adherence, other factors such as documentation or cultural factors were not assessed. Additional research is needed to fully discern the extent to which IVR technology can be used for data collection with specific subgroups of immigrant Latinos. Next, research is needed to evaluate alternative diary periods to effectively capture workers' health and safety behavior, while also avoiding possible threats to data integrity resulting from diary-induced behavior changes (i.e., answering regular questions about behavior may result in different behavior patterns) or habituation to diary surveys over extended periods of time. Finally, this study did not evaluate the overall quality of data obtained from IVR technology. Future research that systematically examines response patterns to individual items and scales across a study period are needed before definitive conclusions can be drawn about using IVR technology for data collection with immigrant Latinos.

Limitations notwithstanding, this study adds to the growing evidence base of the value of IVR as a data collection tool. The evidence suggests that immigrant Latinos can, with minimal prompting adhere to a 21-day diary protocol, and that there are few individual or contextual factors that systematically shape whether or not a participant will adhere. Emphasis on *personalismo* may contribute to enhanced adherence to use of the IVR system. Although additional evaluation research is needed, the overall pattern of results suggests that IVR technology may provide a tool to enable use of daily diary-type study designs for understanding health behaviors among immigrant Latinos.

Table A1. Demographic characteristics by adherence status to the 21-day interactive voice response (IVR) telephone diary.

Characteristics	Sample	“Non-Completers”	“Non-Adherent”	Adherent	p-value
	N (%)	N (%)	N (%)	N (%)	
Sample	119 (100)	29(24.4)	46(38.7)	44(37.0)	
Period					0.0360
1 (9/24/10 – 10/7/10)	60(51.3)	8(13.3)	26(43.3)	26(43.3)	
2 (10/8/10 – 11/1/10)	57(48.7)	19(33.3)	20(35.1)	18(31.6)	
Age					0.4983
19-28	42(35.3)	7(16.7)	20(47.6)	15(35.7)	
29-38	56(47.1)	17(30.4)	18(32.1)	21(37.5)	
≥ 39	21(17.6)	5(23.8)	8(38.1)	8(38.1)	
Marital Status					0.8600
Not married	43(36.1)	13(30.2)	15(34.9)	15(34.9)	
Married, unaccompanied	12(10.1)	2(16.7)	5(41.7)	5(41.7)	
Married, accompanied	64(53.8)	14(21.9)	26(40.6)	24(37.5)	
Educational attainment					0.7405
Primary or less	44(37.0)	8(18.2)	20(45.5)	16(36.4)	
Secondary	50(42.0)	14(28.0)	17(34.0)	19(38.0)	
Preparatory or more	25(21.0)	7(28.0)	9(36.0)	9(36.0)	
Years in the US					0.6603
≤ 7 years	44(37)	13(29.5)	15(34.1)	16(36.4)	
8-15 years	58(48.7)	13(22.4)	22(37.9)	23(39.7)	
≥ 16 years	17(14.3)	3(17.6)	9(52.9)	5(29.4)	
Country of Origin					
Mexico	91(77.0)	26(28.6)	33(36.3)	32(35.2)	0.1559
Other	28(23.0)	3(10.7)	13(46.4)	12(42.9)	

p-values obtained using Chi-Square test

Table A2. Health characteristics of study participants during the baseline interview by adherence status to the 21-day interactive voice response (IVR) telephone diary.

Characteristics	Sample	"Non-Completers"	"Non-Adherent"	Adherent	p-value
	M (SD)	M (SD)	M (SD)	M (SD)	
Physical health					
DASH score	3.4(4.9)	3.5(4.8)	4.2(6)	2.6(3.5)	0.2873
Roland-Morris score	0.3(1.7)	0.4(2.4)	0.1(0.7)	0.5(1.9)	0.5423
PCS	46.4(5.0)	46.5(5.2)	45.7(5.7)	47(4.1)	0.5386
Mental health					
CES-D score	12.9(4.8)	13.3(4.9)	12.9(5)	12.7(4.7)	0.8409
MCS	40.9(8.0)	41.3(9)	40.5(8.2)	41(7.5)	0.9228

p-values obtained using a one-way ANOVA

Table A3. Work and job characteristics of study participants at the baseline interview by adherence status to the 21-day interactive voice response (IVR) telephone diary.

Characteristics	Sample	"Non-Completers"	"Non-Adherent"	Adherent	p-value
	N (%)	N (%)	N (%)	N (%)	
Worker Status					0.0388*
Framer	26(21.8)	11(42.3)	8(30.8)	7(26.9)	
Roofer	35(29.4)	7(20.0)	10(28.6)	18(51.4)	
General Construction	58(48.7)	11(19.0)	28(48.3)	19(32.8)	
	M (SD)	M (SD)	M (SD)	M (SD)	
Hours of work/week	41.9 (9.0)	43.3 (6.9)	41.3 (6.8)	41.5 (11.8)	0.6170
Weeks of construction	37.7 (16.6)	35.6 (15.0)	38.8 (15.5)	37.8 (18.9)	0.7352
Control	6.2 (3.5)	7.1 (3.7)	6.3 (3.6)	5.5 (3.1)	0.1486
Variety	8.4 (2.3)	9.2 (2.4)	8.1 (2.1)	8.1 (2.4)	0.0904
Demand	9.8 (3.1)	9.9 (2.8)	10.0 (3.3)	9.6 (3.2)	0.7880
Perceived Safety Climate	23.0 (5.3)	24.3 (5.5)	22.4 (5.4)	22.7 (5.1)	0.2918
Supervisory Abuse	17.2 (4.2)	18.1 (4.0)	17.2 (4.4)	16.6 (4.0)	0.3117

*p-value obtained using Chi-Square test. Remaining p-values obtained from univariate analysis of variance models, wherein the work characteristic was regressed on participant classification.

Table A4. Agreement with statements about using the interactive voice response (IVR) obtained from debriefing interviews conducted with individuals who accessed the system (n=85)

	Sample (n=85) % (n)	Non- Adherent (n=40) % (n)	Adherent (n=45) %(n)	p-value
<u>Appraisals</u>				
The questions I was asked made sense, given the type of work I do.	99% (84)	100% (40)	98% (44)	.5294
I liked the confidentiality of answering work-related questions to a computer instead of a person.	72% (61)	75% (30)	69% (31)	.5321
The telephone calls were easy.	74% (63)	70% (28)	78% (35)	.4138
I would participate in another study like this one that used the telephone calls.	81% (67)	72% (29)	88% (38)	.0670
<u>Experienced Barriers</u>				
You had problems because the computer did not understand your response to a question.	64% (54)	60% (24)	67% (30)	.5329
You were cut off or had to start the call over for any reason.	38% (32)	38% (15)	38% (17)	.9487
You were not able to become comfortable answering questions asked by a computer.	41% (35)	40% (16)	42% (19)	.8354
Remembering to call each day was hard for me.	47% (40)	68% (27)	29% (13)	.0004
I skipped at least one telephone call because they took too minutes from my cell phone plan.	16% (14)	18% (7)	16% (7)	.8094

Paper #1, References

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Paper #2. Work Safety Climate and Safety Practices among Immigrant Latino Residential Construction Workers

Paper #2, Background

Latino workers in residential construction constitute a large part of an increasingly diverse workforce. In 1992, Latinos represented 14% (0.65 million) of all workers in the construction industry; in 2001, they represented 18% (1.30 million); and in 2007, they represented 30% (2.98 million) [Dong et al., 2010a]. About one million of the Latino construction workers speak only Spanish [Brunette, 2004].

The construction industry has among the highest occupational injury and fatality rates of all US industries [Bureau of Labor Statistics, 2007]. These injury and fatality rates are greater for immigrant Latino workers than for non-immigrant workers [Dong & Platner, 2004]. For example, from 2001 to 2008, the death rate by falls for foreign-born Latino construction workers was 6.0 per 100,000 full-time equivalents (FTE), a rate 58% greater than the rate of 3.8 per 100,000 FTEs for white, non-Latino workers [Center for Construction Research and Training, 2008]. The number of non-fatal illness and injuries to Latino construction workers varies based on trade. From 2008 to 2010, the rate of non-fatal illness and injuries involving days away from work for Latino construction workers in two of the most hazardous construction trades, ironworker and roofer, exceeded that of non-Latino construction workers [Bureau of Labor Statistics, 2010]. Construction industry illness and injury rates are underestimated [Azaroff et al., 2002], particularly for Latino construction workers working for small firms [Dong et al., 2011].

Work safety climate is the perception by workers of the emphasis employers place on safety over production. Work safety climate is often associated with occupational safety performance and reduced occupational injuries [Neal & Griffin, 2002; Zohar, 2010]. Among construction workers, work safety climate has been shown to be related to work pressure demands, and to the frequency and severity of injuries and fatalities [Gillen et al., 2002; [Shoji & Egawa, 2006](#); Choudhry et al., 2007]. However, little attention has been paid to work safety climate among Latino construction workers. Menzel and Gutierrez [2010] identified perceived risks among Latino construction workers in southern Nevada. These perceived risks included economic pressure, exploitation, immigrant status, and traditional values. As with other studies of immigrant Latino workers [Arcury et al., 2012; Keifer et al., 2009; Grzywacz et al., 2007; Quandt et al., 2006], Menzel and Gutierrez [2010] note that Latino construction workers accept unsafe working conditions for several reasons. They fear job loss when they are supporting families in the US and in Mexico, they may be undocumented and do not wish to interact with anyone who might represent the government, and they have a belief system in which men are expected to accept danger and act as if they will not be harmed by exposure to hazards. Thus, work safety climate is an especially important consideration for improving the safety of immigrant workers such as Latino residential construction workers.

This analysis examines work safety climate among Latino residential construction workers. Its three aims are to: (1) describe work safety climate among Latino residential construction workers using the Perceived Safety Climate Scale [Gillen et al. 2002]; (2) delineate differences in work safety climate items and score by worker personal and employment characteristics; and (3) determine associations of the work safety climate score with specific work safety behaviors.

Paper #2, Methods & Materials

The study was conducted in western North Carolina as a partnership among the Center for Worker Health, Wake Forest School of Medicine; Myers-Lawson School of Construction, Virginia Polytechnic Institute and State University; and Hogar Latino (HOLA) of Wilkes County. This analysis is part of a broader project designed to determine the feasibility of using Interactive Voice Response (IVR) technology to collect daily diary data from Latino residential construction workers. The research protocol was approved by the Wake Forest School of Medicine Institutional Review Board and participants provided signed informed consent.

Sample. Latino residential construction workers were recruited in Wilkes and surrounding western North Carolina counties using a non-probability design. No list of Latino residential construction workers or their employers exists. Therefore, HOLA project staff used a combination of techniques to recruit residential construction workers, including identifying known individuals within existing social networks, snowball, and referral. Inclusion criteria included age 18 years or older, Latino (self or parents born in a Latin American country, or self-identified as “Latino” or “Hispanic”), and usual employment for 35 or more hours per week working in residential construction. The recruitment goals were targeted to secure a balanced representation of framers, roofers, and general construction workers (concrete, drywall, masonry, etc.). Participants who completed a baseline questionnaire (n = 119) were asked to complete a 21-day cycle of work daily diary using an IVR questionnaire (n = 90). Participants were given a \$15 incentive for completing the baseline questionnaire. Participants received up to a \$73 incentive for completing the 21 day call-in cycle for the work daily diary IVR questionnaire.

Data Collection. Data collection included two phases: a baseline interviewer-administered questionnaire; and a work daily diary follow-up based on an IVR questionnaire. Participants who completed the baseline questionnaire were asked to participate in the work daily diary follow-up. Data collection for the baseline interviews and work daily diary follow-up was completed from September 23, 2010 through November 23, 2010.

The baseline questionnaire included participant demographic data; a physical demands inventory, including occupational characteristics (e.g., years in construction, primary tasks performed in construction); health history (e.g., presence of chronic conditions); and organization of work characteristics, including work safety climate, workplace personal protection equipment, and abusive supervision. The work daily diary questionnaire focused on daily well-being, job tasks, injuries, general safety behavior, psychological workload, abusive supervision, and the use of personal protection equipment. The baseline and work daily diary questionnaires used translated Spanish language instruments when available, including the Perceived Safety Climate Scale [Gillen et al., 2002]. English language instruments and items developed for this project were translated into Spanish by a native Spanish-speaker. All items were then back translated into English by a native English-speaker. Discrepancies identified in the back translation were corrected through consensus and incorporated into both the Spanish and English versions of questionnaires [Behling & Law, 2000].

The work daily diary questionnaire was adapted for the IVR system. This system guided participants through a series of questions about daily health symptoms, and a variety of work-related experiences and exposures. The system was programmed with one question asking whether the participant worked in construction for pay that day, which allowed all construction-related questions to be skipped on non-work days. Participants provided responses to each question using voice or keypad responses.

Baseline questionnaires were collected by trained native Spanish-speaking interviewers. Training consisted of a thorough review of study purpose, screening and recruitment procedures, line-by-line review of the interviewer-administered questionnaires, and progressively more realistic practice interviews. Completing the baseline questionnaire took an average of 48 minutes. Participants were instructed in the use of the IVR system after completing the baseline questionnaire. Participants were asked to complete the work daily diary questionnaire for 21 consecutive days by calling a specific telephone number and responding to the questions asked. The duration of the call-ins varied based on the individual responses and subsequent as-needed follow-up questions. The average length of the call during work days was 13.6 minutes (SD=3.2), while the average call length on non-work days was 3.5 minutes (SD=3.8).

Measures. Work safety climate was measured based of the 10-item Perceived Safety Climate Scale [Gillen et al., 2002]. This instrument was derived from scales developed by [Dedobbeleer and Beland \[1991\]](#), and [Zohar \[1980\]](#). The Perceived Safety Climate Scale was modified to allow for ease of language translation and automated telephone responses. The first nine items used a four-point Likert scale (strongly disagree to strongly agree) for statements about workplace safety practices. The final item asked for an overall appraisal of their organization’s commitment to safety and provided three response options, “Supervisors do as much as

possible to make my job safe,” “Supervisors could do more to make my job safe,” and “Supervisors are only interested in doing the job fast and cheap.” The item responses were summed for all 10 questions for a total score ranging from 10 to 39. A higher score indicated that the participant perceived a safer work environment. Cronbach’s alpha was 0.78 for the baseline sample and 0.75 for the work daily diary sample.

A list of five individual safety practices and five collective safety practices were derived from an assessment of trade specific safety practices; hazard checklists and mitigation best practices; industry best practices literature; occupational safety and health literature; and academic research on trade specific hazards and incident types [Fredericks et al., 2005; Louisiana Workers' Compensation Corporation, 2007; [Occupational Safety and Health Administration](#), 2009]. Items in the work daily diary questionnaire asked if each safety practice occurred that day (Appendix). For each day the work daily diary questionnaire was completed, dichotomous measures of individual safety practices included no ladder safety risks, no carrying-related safety risks, no scaffolding-related safety risks, no glove-related safety risks, and did not do something known to be unsafe. Dichotomous measures of collective safety practices included attended a daily safety meeting, reported a safe and orderly worksite, had all necessary safety equipment, did not need to use damaged equipment, and did not see a coworker create an unsafe situation.

Personal characteristics included age in years, years lived in the US, and years lived in North Carolina. Work characteristics include average number of weeks worked in residential construction in the previous year, usual hours per week worked in residential construction, completion of an apprenticeship or other training program, and trade in the categories of framer, roofer or general construction. Finally, participant work arrangement was put into the categories stable (construction contractor or subcontractor; worked for the same contractor or subcontractor for 3 months or longer) and unstable (worked for more than one contractor or subcontractor during the past 3 months).

Analysis. Analysis of variance techniques were used to test for differences among groups (e.g., roofers, framers, general construction workers, completed an apprenticeship or not) on items relating to worker safety climate. Associations between the Work Safety Climate Score and personal characteristics were assessed using Spearman’s Correlation coefficient. To assess the level of association between the Work Safety Climate Score and individual and collective safety practices, Spearman correlation coefficients were also used. All tests were deemed significant at $p < 0.05$.

Paper #2, Results

Personal and Employment Characteristics. The sample included 119 male Latino residential construction workers from western North Carolina (Table 1B). Of the 119 participants who completed the baseline questionnaire, 90 completed at least one work daily diary. Participants completed from one to 21 work daily diary questionnaires, with 44 participants (37.0% of total sample) completing fewer than 18 of the 21 days, and 46 participants (38.7%) completing 18 or more of the 21 days.

The personal and employment characteristics of the baseline interview sample and the work daily diary sample were similar. The mean age in both samples was 32.2 years. The participants in both samples had lived in the US for 10 years, and in North Carolina for 8 years. They worked an average of about 35 weeks in the previous year in residential construction, and they worked about 41 hours in the previous week. About 22% of the participants had completed an apprenticeship or other training. About 30% of the participants were framers, about 20% were roofers, and about half were general construction workers. About three-quarters had stable work.

Work Safety Climate. Participants reported variation in the different work safety climate items (Table 2B). Most agreed with the statements that workers have almost total control of their personal safety (78.2%), that workers are regularly made aware of dangerous work practices or conditions (71.4%), that proper safety equipment is always available (68.9%), and that taking risks is not part of their jobs (62.2%). However, few workers agreed with the statement that they receive instructions on safety when hired (31.1%), that workers are regularly praised for safe conduct (29.4%), or that workers attend regular safety meetings (25.2%). Most

agreed with the statement that they are likely to be injured in the next 12 months (84.0%). Only 40.3% of participants reported that their employer does as much as possible to make their jobs safe. The mean summary score for work safety climate was 23.0.

Participants varied by trade in their agreement with most of the work safety climate items. In general, framers and general construction workers reported significantly greater agreement with work safety climate items than did roofers. For example, although 92.3% of framers and 81.0% of general construction workers agreed with the statement that workers have almost total control over their personal safety, 62.7% of roofers agreed with this statement. Although 88.5% of framers and 72.4% general construction workers agreed with the statement that workers' safety practices were very important to management, 51.4% of roofers agreed with this statement. The mean summary score for work safety climate was 24.3 for framers and for general construction workers, but it was 19.9 for roofers.

The summary score for work safety climate was associated with several participant characteristics for both the baseline interview sample and for the work daily diary sample (Table 3B). Age had a significant positive association with work safety climate for the work daily diary sample. Years in the US and years in North Carolina both had significant positive associations with work safety climate for both samples. Trade was significantly associated with work safety climate in both samples such that roofers had lower scores (19.9 for roofers in the total sample, 19.4 for roofers in the work daily diary sample), than framers (24.3 and 24.0, respectively) or general construction workers (24.3 and 24.0, respectively).

Days reported for several individual and collective safety practices were associated with the work safety climate score (Table 4B). This analysis is limited to the work daily diary sample. Days reporting no glove-related safety risks and not doing something known to be unsafe are two individual safety practices with significant positive associations with the work safety climate score. Days reporting not needing to use damaged equipment was a collective safety practice with a significant positive association with the work safety climate score. Days engaging in two additional collective safety practices, attending a daily safety meeting and not seeing a coworker create an unsafe situation were associated with the work safety climate score at the trend level.

Paper #2, Discussion

These results expand knowledge about the importance of work safety climate for the occupational safety of Latino residential construction workers. This is among the first studies to measure work safety climate among Latino residential construction workers and to delineate statistical associations of work safety climate with participant personal and work characteristics. Other research on Latino construction workers' perceptions of work safety climate has been based on qualitative analyses [Menzel & Gutierrez, 2010; Roelofs et al., 2011]. Examination of the individual items in the work safety climate scale reflects the results of these qualitative analyses in behaviors that reflect exploitation, immigrant status, and traditional values. Few report that they receive instructions on safety when hired, that they attend regular safety meetings, or that they are praised for safe behaviors. Most believe they will be injured in the next year. Only about 2 in 5 believe that supervisors do as much as possible to make the job safe.

Second, these results document that work safety climate is not uniform across Latino construction workers but varies by the type of work in which they are engaged. Specifically, roofers report a much lower work safety climate than do participants who are framers or general construction workers. Previous research examining work safety climate among construction workers has considered differences by personal characteristics, union status, work site, and in specific trades [Choudhy et al., 2009; Gillen et al., 2002; Kaskutas et al., 2009; Shoji & Egawa, 2006]. This is the first to compare work safety climate by trade. It shows that roofers consistently do not agree with the items included in the work safety climate scale. Roofing is the construction trade with the highest number of fatalities (34.7/100,000 FTEs) [Bureau of Labor Statistics, 2010].

Finally, these results show that work safety climate among Latino construction workers is associated with the individual and collective safety behaviors in which they engage. This is consistent with analyses of work safety

climate that documents its association with worker safety [Zahor, 2010], and offers evidence that the creation of a culture or climate of safety may be essential to ensuring that workers protect themselves and each other on the job site.

Age and years of residence in the US and in North Carolina are also associated with work safety climate [Dong et al. 2009, 2010b]. These factors indicate the importance of experience for understanding safe work climate, and they suggest that younger workers and recent migrants are most 'at risk' for employment by contractors who minimize safety.

This research should be evaluated in light of its limitations. The sample was small, it was not randomly selected, it was limited to one area of one state, and it experienced a sizeable loss in those completing the work daily diary questionnaire. Each of these factors limits the generalizability of the results. Measures of individual and collective safety practices are self-reported. However, the study includes longitudinal data reporting safety behaviors reported daily using an electronic reporting protocol. It also considered several residential construction trades which face different occupational hazards.

Implications. These results have implications for occupational safety practice and research. Improving work safety climate will improve work safety for Latino residential construction workers [Brunette, 2004; Zohar, 2010]. Improving work safety climate needs to consider procedures to address safety for different construction trades. Improvements in work safety climate for Latino residential construction workers will require improved safety training for these workers [O'Connor et al., 2005]. This training should include information on safety practices and on current safety regulations. This improvement also requires training of employers and supervisors so that they support work safety for their employees. Finally, it will require greater enforcement of existing regulations for an industry in which work is spatially dispersed and often hidden.

This is the first statistical research on work safety climate among Latino residential construction workers. These results build on qualitative analyses of perceptions of work safety among these workers [Menzel & Gutierrez, 2010; Roelofs et al., 2011]. This study shows the potential importance of understanding work safety climate for determining safety practices among these workers. However, the number of participants and the number of trades they represent is limited. The IVR technology allowed the collection of longitudinal data that enhanced determining the association between work safety climate and safe work practices. Research is needed to verify and extend these results. Larger samples of workers and different trades need to be included. Future research should include comparisons with workers of other ethnic groups to see if risks differ among these groups. Additionally, a focused study of work safety climate among roofers is warranted. A longer period for following workers, along with additional variables, will improve determining causal relationships.

Conclusion. Work safety climate is associated with safety behaviors among Latino residential construction workers. Variation in work safety climate by trade indicates that addressing safety is especially needed among those employed as roofers. Interventions are needed to improve safety training among those who employ Latino construction workers as well as the workers themselves. Further research should expand the number of workers and trades involved in analyses of work safety climate.

Table 1B: Personal and Employment Characteristics, Latino Residential Construction Workers, Western North Carolina, 2010-2011.

Personal and Employment Characteristics	Total Sample n = 119		Work Daily Diary Sample n = 90	
	Mean	SD	Mean	SD
Age (in years)	32.2	8.2	32.2	8.5
Years Lived in the US	10.0	6.3	10.2	6.4
Years Lived in North Carolina	8.0	5.1	8.2	5.3
Average Weeks Worked in Residential Construction in the Previous Year	35.4	13.1	35.4	12.5
Usual Hours Worked per Week in Residential Construction	41.5	7.9	40.9	8.2
	n	%	n	%
Completed an Apprenticeship or Other Training Program	26	22.2	19	21.6
Trade				
Framer	35	29.4	28	31.1
Roofer	26	21.8	15	16.7
General Construction	58	48.7	47	52.2
Work Arrangement				
Stable	88	73.9	69	76.7
Unstable	31	26.1	21	23.3

Table 2B. Individual Work Safety Climate Items* and Work Safety Climate Score by Trade, Latino Residential Construction Workers, Western North Carolina, 2010-2011.

Work Safety Climate Items	Sample n=119		Framers n=26		Roofers n=35		General Construction Worker n=58		p-value
	n	%	n	%	n	%	n	%	
Workers' safety practices are very important to management	83	69.7	23	88.5	18	51.4	42	72.4	< 0.01
Workers are regularly made aware of dangerous work practices or conditions	85	71.4	20	76.9	20	57.1	45	77.6	0.08
Workers are regularly praised for safe conduct	35	29.4	6	23.1	2	5.7	27	46.6	< 0.01
Workers receive instructions on safety when hired	37	31.1	9	34.6	4	11.4	24	41.4	< 0.01
Workers attend regular safety meetings	30	25.2	7	26.9	3	8.6	20	34.5	0.02
Proper safety equipment is always available	82	68.9	19	73.1	21	60.0	42	72.4	NS***
Workers have almost total control over personal safety	93	78.2	24	92.3	22	62.9	47	81.0	0.01
Taking risks is not a part of my job	74	62.2	21	80.8	9	25.7	44	75.9	<0.01
The possibility of being injured at work in the next 12 months is very likely.	100	84.0	23	88.5	29	82.9	48	82.8	NS
Supervisors do as much as possible to make my job safe**	48	40.3	11	42.3	14	40.0	23	39.7	NS
Summary Score	Mean 23.0	SD 5.3	Mean 24.3	SD 4.8	Mean 19.9	SD 5.6	Mean 24.3	SD 4.7	<0.01

*Strongly agree and agree

**Versus those who responded, "they could do more to make my job safe" or "they are only interested in doing the job fast and cheaply"

***Not significant

Table 3B: Associations of Personal and Employment Characteristics with Work Safety Climate Score, Latino Residential Construction Workers, Western North Carolina, 2010-2011.

Personal and Employment Characteristics	Total Sample n = 119		p-value	Work Daily Diary Sample n = 90		p-value
	Correlation with Work Safety Climate Score *			Correlation with Work Safety Climate Score *		
Age (in years)	0.16		0.07	0.21		0.04
Years Lived in the US	0.25		<0.01	0.34		<0.01
Years Lived in North Carolina	0.18		0.04	0.26		0.01
Average Weeks Worked in Residential Construction in the Previous Year	0.04		NS**	0.01		NS
Usual Hours Worked per Week in Residential Construction	0.18		0.05	0.15		NS
	Mean Work Safety Climate Score	SD		Mean Work Safety Climate Score	SD	
Completed an Apprenticeship or Other Training Program						
Yes	24.23	4.63	NS	23.90	4.86	NS
No	22.70	5.53		22.26	5.35	
Trade						
Framer	24.31	4.76	<0.01	24.00	4.75	<0.01
Roofer	19.88	5.59		19.39	4.42	
General Construction	24.31	4.66		24.00	5.04	
Work Arrangement						
Stable	22.96	5.62	NS	22.68	5.36	NS
Unstable	23.13	4.47		22.24	4.85	

*Spearman correlation coefficients

**Not significant

Table 4B. Association of Work Safety Climate Score with Observed Work Days for which Individual and Collective Safety Practices Were Reported, Latino Residential Construction Workers, Western North Carolina, 2010-2011.

	Work Safety Climate Score	
	Coefficient	p-value
Individual Safety Practices		
No ladder safety risks	.09	NS*
No scaffolding-related safety risks	-.05	NS
No carrying-related safety risks	-.02	NS
No glove-related safety risks	.21	.04
Did not do something known to be unsafe	.24	.02
Collective Safety Practices		
Attended a daily safety meeting	.19	.07
Reported a safe & orderly worksite	-.00	NS
Had all necessary safety equipment	-.01	NS
Did not need to use damaged equipment	.26	.01
Did not see a coworker create an unsafe situation	.20	.06

Sample consists of participants with one or more work-day diary entries (n=90).

*Not significant

Paper #2, References

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Paper #3. Occupational Injury and Work Organization among Immigrant Latino Residential Construction Workers

Paper #3, Background

Injury is a major occupational health problem in the construction industry. Although overall rates of non-fatal injury have declined over the past decade [Center for Construction Research and Training (CPWR) 2008], construction workers continue to experience 4.2 injuries per 100 full-time equivalents [Bureau of Labor Statistics (BLS) 2010]. Within the construction industry, the burden of injuries is elevated among different trades and worker groups. Among residential construction workers, injury rates are elevated among roofers relative to other trades, although general construction workers report the highest absolute number of injuries [CPWR, 2008]. Injury rates are also elevated among Latinos compared to their non-Hispanic white counterparts [Dong and Platner, 2004; Dong et al., 2010]. Estimated injury rates, those within and outside of the construction industry, are from the Survey of Occupational Injuries and Illnesses (SOII), which is based on employers' Occupational Safety and Health Administration (OSHA) logs that must be completed by employers with more than 10 employees. Cases are recordable if they result in death, loss of consciousness, days away from work, restricted work activity or job transfer or medical treatment beyond first aid.

There is general agreement that published injury rates undercount actual injury experience [Azaroff et al., 2002; Boden and Ozonoff, 2010; Schoenfisch et al., 2010], including injury counts in construction [Dong et al., 2011]. Several factors contribute to injury undercounting, including the incomplete scope in the coverage of workers, incomplete capture of reported injury cases, and unreported cases [Ruser, 2010] which can result from employer and employee disincentives to report an injury [Leigh et al., 2004]. Many of the disincentives are particularly salient for immigrant Latino workers, many of whom prefer to remain anonymous rather than risk potentially offending an employer or being identified by presumed authorities [Quandt et al., 2006; Menzel and Gutierrez, 2010]. Despite widespread recognition of undercounting of actual occupational injuries inside and outside the construction sector, the potential magnitude of underreporting remains ambiguous. Dong et al. [2011] recently reported that official data sources underreport severe injuries to construction workers by 40–75%, and an earlier study concluded that construction injury rates are twice that reported in official statistics [Glazner et al., 1998]. Work organization is receiving increased attention in occupational health in general and in injury prevention more specifically. Work organization refers to the way that work gets done; it draws attention to the way that jobs are designed and performed (i.e., work processes), management and human resource policies, production methods used, as well as broader labor market policies [Sauter et al., 2002]. The potential value of work organization in understanding injury and injury prevention is informed, at least in part, by evidence suggesting that work organization factors play a role in safety violations [Alper and Karsh, 2009].

The potential value of work organization is also drawing increased attention because it likely underlies or enables more proximal and direct exposures on the job. For example, evidence suggests that a poor commitment to safety creates greater risk opportunity because of workers' greater exposure to hazardous equipment and practices [Beus et al., 2010]. Moreover, work organization creates additional exposures that are frequently "invisible" (e.g., occupational stressors), but nonetheless can contribute to excess injury through preoccupation, disregard for safety procedures and other mechanisms [Christian et al., 2009]. Thus, work organization is an important element of injury prevention because it likely creates systematic work exposures and it creates additional exposures that can contribute to excess injury [Benach et al., 2010; Commission on Social Determinants of Health, 2008]. Research linking work organization to injury in the construction industry is sparse. Work scheduling, an area of work organization examining the temporal structure of construction work, has been linked with health and safety outcomes [Goldenhar et al., 2003; Dong, 2005]. Shimazu and de Jonge [2009] documented an association between effort-reward imbalance, a measure of job stress, and greater risk for physical complaints among Japanese construction workers. The risk of recurrent low back pain over a 3-year period was elevated for scaffold workers with high levels of psychological demand, another measure of job stress, and low levels of worker control [Elders and Burdorf, 2004]. Although construction

managers recognize the importance of work organization in maintaining safety [Torner and Pousette, 2009], research focused on the potential implications of work organization for worker injury remains in need of empirical attention [Schulte, 2006; Murie, 2007].

The goal of this study is to enhance understanding of burden of occupational injury and the work organization factors underlying non-fatal injury among immigrant Latino residential construction workers. To accomplish this goal we use longitudinal data obtained from a community-based sample of Latino residential construction workers ($n = 107$) in selected trades to: (i) document 3-month incidence of work-related injury among Latino residential construction workers, and variation in incidence by age, time in the US, country of origin, and construction trade; (ii) describe work organization characteristics of these workers, including variation in job structure (i.e., work hours, precariousness), job design (i.e., skill variety, control, psychological demands, hazards exposure), supervisory practices (i.e., power, retaliation, ability to communicate), and safety climate experiences; (iii) explore variation in injury risk attributed to work organization characteristics.

Paper #3, Methods and Materials

The data for this study are from a broader project designed to determine the feasibility of using Interactive Voice Response (IVR) technology to collect daily diary data from Latino residential construction workers. The original project involved four separate data collection components: a baseline interviewer administered survey, a 21-day daily diary period using IVR technology, a debriefing interview at the end of the diary period, and a follow-up interview 3 months after completing the diary period. The current paper uses data from the baseline and the 3-month follow-up interviews.

Sample. Baseline data were obtained from a non-probability sample of residential construction workers who self identified as Latino ($N = 119$). Participants were recruited in partnership with Hogar Latino (HOLA) of Wilkes County, a non-profit organization that serves the Latino communities of Wilkes and surrounding counties in western North Carolina. HOLA staff recruited residential construction workers through a combination of techniques including known individuals within existing social networks, snowball, and referral. Study inclusion criterion were age 18 years or older, Latino (self or parents born in a Latin American country, or self-identified as “Latino” or “Hispanic”), and employment for 35 or more hours per week in construction. There were no exclusion criteria. Three-month follow-up interviews were obtained from 107 study participants (89.9%).

Data Collection. The baseline interviewer-administered interview assessed stable attributes of the individual (e.g., age, country of origin), occupational characteristics (e.g., years in construction, primary tasks performed in construction), health history (e.g., presence of chronic conditions), and multiple aspects reflecting the organization of work (e.g., control, psychological demands, perceived exposure to hazards, see Measures section). The baseline interview took, on average, 48 min to complete, and participants received a \$15 incentive. The follow-up interview focused primarily on experiences of injury and changes in health during the preceding 3-month period. The follow-up interview took 24 min, on average, to complete, and participants received a \$25 incentive. All participants provided signed informed consent before any data were collected. All recruitment and data collection activities were approved by the Wake Forest School of Medicine Institutional Review Board (FWA #00001435).

The content of the baseline and follow-up interviewer-administered survey questionnaires underwent thorough translation and back-translation procedures. Content from validated Spanish instruments was used without modification when they were available. English-only instruments and items developed for this project were translated into Spanish by a native Spanish-speaker. All items were then back translated into English. Discrepancies identified in the back translation were corrected through consensus and incorporated into both the Spanish and English versions of questionnaires [Behling and Law, 2000]. Survey questionnaire data (i.e., baseline and 3-month follow-up) were collected by four trained interviewers. All interviewers were native Spanish-speakers. Training consisted of a thorough review of study purpose, screening and recruitment procedures, line-by-line review of the interviewer-administered questionnaires, and progressively more realistic

practice interviews.

Measures. Injury incidence, the primary dependent variable, was assessed by asking participants whether they had experienced five specific types of injuries (i.e., sprains or strains, cut or laceration, flame or chemical burn, bruise or contusion, broken or fractured bone, dislocation) and one additional question asking about whether the participant had experienced any other type of injury in the past 3 months while performing paid construction work. Individuals who answer “yes” to one or more injuries in the past 3 months were then asked “How many days after [INSERT INJURY/your most serious injury] did you go back to work?”. Response options were “same day/did not take off from work,” “the day after the accident,” separate response options for the second, third, and fourth “day after the accident,” “the fifth day after the accident or longer” and “still off paid work.” Individuals reporting returning to work on the second day after the accident or longer were classified as having experienced an injury requiring time off from work.

Work organization variables were organized into three categories. The first category is structural attributes of the construction job and is evaluated with two variables. The first, long work hours, was constructed based on the average number of hours typically worked in construction and dichotomized such that those working 45 or more hours per week were coded one, zero otherwise. The second structural characteristic of the construction work job, precarious employment, was measured with a single question asking “which statement best describes your work arrangement in construction” with three response options: “I am a construction contractor or subcontractor and do trades work myself,” “I have worked for the same contractor or subcontractor for 3 months or longer,” and “I have worked for several contractors or subcontractors during the past 3 months.” Individuals who reported working for several individuals in the past 3 months were coded one for precarious employment, all others were coded zero.

The job design category of work organization was assessed using a modified version of the Job Content Questionnaire (JCQ) [Karasek and Theorell, 1990] and included four variables. Control was assessed with 3 items asking about opportunities to exert control over work (e.g., “How often are you allowed to make your own decisions about your work?”). Variety was assessed with 6 items probing how jobs vary in content, location, and routine (e.g., “How often do you do a variety of different things on your job?”). Psychological demand was assessed with 9 items asking about the job-related stressors (e.g., “How often is your job hectic?”). Exposure to perceived hazards was assessed with 6 items asking about the frequency participants encountered environmental hazards (“How often does your job require you to work in areas where you are exposed to fire, burns, or shocks?”) or dangerous equipment (e.g., “How often does your job require working with tools, machinery or equipment that could be dangerous?”) while working in construction. Response options for each item in the modified JCQ ranged from “seldom or never = 1” to “almost always = 4”). Each variable was constructed by summing items so that higher values indicated greater levels of the attribute. This modified instrument has been used in previous research with immigrant Latino workers where the reliability of each set of items, assessed via Cronbach’s alpha, ranged from a low of 0.72 to a high of 0.79, suggesting good reliability [Grzywacz et al., 2007].

The supervisory practices category of work organization was assessed with several instruments to obtain four variables. First, two aspects of supervision were assessed using an established scale [Tepper, 2000] that has been used in previous research with immigrant Latino workers [Grzywacz et al., 2007, 2010; Mari’n et al., 2009]. Powerful influence reflects the extent to which workers believe their supervisor can shape or influence their opportunities on the job was assessed with 4 items (e.g., “My supervisor could. . . influence my getting a pay raise,” or “. . . provide me with special benefits”). Retaliatory supervision was assessed with 3 items asking about the extent to which workers believe that supervisors use their authority to punish workers (e.g., “My supervisor could. . . give me undesirable job assignments” or “Make things unpleasant here”). Response options ranged from “strongly disagree . 1” to “strongly agree . 4.” Both the powerful influence and the retaliatory supervision variable were constructed by summing items so that higher values indicated greater levels of the attribute. Poor communication with supervisors was assessed with a single item from the JCQ asking “how well are you able to communicate with your immediate supervisor?” Possible responses were

“very well,” “somewhat,” and “not at all;” individuals who reported “somewhat” or “not at all” were coded one for having poor communication, all others were coded zero. Safety climate, reflecting management’s commitment to maintaining a safe worksite, was assessed using the 10-item Perceived Safety Climate Scale [Gillen et al., 2002]. Items are scored such that higher values indicate greater management involvement in safety and health.

Personal characteristics. Age (measured in years) and educational attainment assessed based upon the grading system used in Latin American countries (i.e., Primaria, Secundaria, Preparatoria, Universidad) were assessed. Country of origin was obtained. Participants were classified into one of three construction trades. Individuals were classified as being a framer if they were usually involved in building or assembling floors, walls, or roofs using lumber or light gauge metal framing at least 3 days per week. Participants were classified as roofers if they were usually involved in applying roof shingles, removing existing roof shingles, applying hot roofing tar or built up roofing, or carrying roofing materials onto a roof at least 3 days per week. Individuals who self identified as being a general construction worker and did not meet the definition of “framer” or “roofer” were classified as being a general construction worker. Finally, participants were asked if they had ever completed an apprenticeship in any construction trade.

Analysis. The number of injuries observed during the study was assumed to follow the Poisson distribution. The observed incidence rate was calculated as: (total # of injuries)/(total number of hours worked during the 3 month period). This rate is the injury rate per person per 1 h worked. The total number of hours worked during the 3 month period was calculated based on data obtained at the three month follow- up interview wherein all participants (including those who are self-employed contractors or subcontractors) reported the total number of weeks worked since the baseline interview, and the average number of hours worked each week; the resulting figure was 26,492. Reported injuries and work exposure were not “annualized”: all estimates were based on the observed number of injuries and the observed work exposure. The exact confidence interval method was used to calculate the 95% confidence intervals. Projected estimates of injury rates for the 3-month period (13 weeks) for 100 persons, each employed 40 h per week (equating to 52,000 h worked total), were calculated by multiplying the total hours by the lower and upper confidence limits of the injury rate.

Univariate statistics including percentages and means and standard deviations were calculated to describe the organization of construction work. Comparisons of work organization factors among framers, roofers and general construction workers were evaluated using Chi-square or **F**-test statistics for work organization factors with discrete and continuous distributions, respectively. A series of logistic regression models were fit to explore the prospective bivariate association of each work organization factor, assessed during the baseline interview, with work injury assessed at the follow-up interview. Each bivariate model was then expanded to control for worker type and total work exposure during the observation period. All analyses were performed using SAS v9.2 (SAS Institute, Cary, NC), and used a Type I error rate of 0.05.

Paper #3, Results

TABLE I. Work-Related Injury in the Past 3 Months by Personal Characteristics

	Sample(N = 119)	Follow-up sample (n = 107)		P-value ^a
	N (%)	Uninjured (n = 79)	Injured (n = 28)	
Age				0.6274
≤ 35 years	79 (66)	52	17	
> 35 years	40 (34)	27	11	
Years in the US				0.4663
≤ 10 years	58 (49)	36	15	
> 10 years	61 (51)	43	13	
Educational attainment				0.3016
≤ Secondary (9th grade)	62 (52)	39	17	
> Secondary	57 (48)	40	11	
Country of origin				0.6360
Mexico	91 (76)	60	20	
Other	28 (24)	19	8	
Construction trade				0.0187
Framer	26 (22)	12	7	
Roofer	35 (29)	20	13	
General labor	58 (49)	47	8	
Apprenticeship				0.1042
No	91 (78)	66	19	
Yes	26 (22)	12	8	

^aP-value obtained using Chi-Square test.

Participants were, on average, 31.7 years of age (SD = 7.6). Most had little formal education; 37.4% (n = 40) of the sample reported a primary education or less (equivalent to 6th grade in the US) while 42% (n = 45) reported having up to a secondary education (equivalent to 9th grade in the US). On average, participants had been in the US for 9.7 years (SD = 6.0), and Spanish was the dominant language for nearly all participants (n = 100, 93.5%). Nearly one-quarter of the sample (22.4%) reported having completed an apprenticeship. Most workers (n = 73, 68.2%) indicated that the statement “I have worked for the same contractor or subcontractor for 3 months or longer” best characterized their connection with the construction industry, while a sizeable minority (n = 29, 24.4%) indicated that the statement “I have worked for several contractors or subcontractors during the past 3 months” described their recent construction work experiences. At the baseline survey participants worked an average of 38.3 weeks (SD = 16.9) in construction in the previous year, and an average of 42 h per week (SD = 8.6). Participants reported working, on average, 7.7 weeks (SD = 3.3) of the 12-week period preceding the follow-up interviews, and typically working 34.2 h per week (SD = 12.7) on the weeks construction was performed during that period.

Twenty-eight participants reported a work-related injury during the observation period prior to the follow-up interview. Injuries included broken or fractured bone (n = 4), dislocation (n = 3), sprain or strain (n = 7), flame or chemical burn (n = 1), as well as cuts or lacerations, and bruises or contusions. The observed injury rate for the 3-month period was 55.0 (95% CI = 41.4–71.6) injuries per 100 FTE (i.e., 28/26,492 = 52,000). If only broken or fractured bones, dislocations or burns are counted (n = 8), the observed incidence rate was 15.7/100 FTE (95% CI = 3.4–15.8). Two of the reported injuries involved two or more days away from work, resulting in a rate of 3.9 lost time injuries per 100 FTE (95% CI = 0.2–7.2). Injury risk among Latino residential construction workers did not differ by age, years in the US, educational attainment or country of origin (Table I). However, injuries were more frequent among roofers than framers or general construction workers ($P < 0.02$).

Substantial variation exists in work organization among Latino residential construction workers (Table II). Fully one-fifth of participants worked long hours, and one-quarter reported having precarious employment. Average levels of control and exposure to hazardous conditions were near the midpoint of the range of possible scores (i.e., range of 3–12 and 6–24, for control and hazardous conditions, respectively), while average levels of skill variety and psychological demand were below the midpoint of the range of possible scores (i.e., range of 6–24 and 9–36 for skill variety and psychological demand, respectively). Average levels of powerful influence and retaliatory supervision were also at the midpoint of the possible range of scores (i.e., range of scores was 4–16 and 3–12 for powerful influence and retaliatory supervision, respectively). One-fifth of participants were unable to communicate with their supervisor. Average perceived safety climate scores approached the possible midpoint of the range of possible values (i.e., 10–39).

TABLE II. The Organization of Work Among Latino Residential Construction Workers in Western NC (N = 119)

	Construction trade							
	Sample(n = 119)		Framer(n = 26)		Roofer(n = 35)		General Laborer(n = 58)	
	N (%)	M (SD)	N (%)	M (SD)	N (%)	M (SD)	N (%)	M (SD)
Job structure								
Long work hours ^{*,†}	25 (21.2)		10 (38.5)		6 (17.6)		9 (15.5)	
Precarious [†]	31 (26.1)		9 (34.6)		8 (22.9)		14 (24.1)	
Job design								
Skill variety ^{**,‡}		8.4 (2.3)		8.7 (2.1)		7.4 (1.8)		8.8 (2.6)
Control ^{*,‡}		6.2 (3.5)		5.5 (3.2)		5.3 (3.2)		7.1 (3.6)
Psychological demand [‡]		9.8 (3.1)		9.1 (2.4)		9.5 (3.4)		10.3 (3.2)
Hazards ^{*,‡}		17.2 (5.1)		16.1 (5.0)		19.2 (5.1)		16.6 (4.9)
Supervisory practices								
Powerful influence ^{***,‡}		10.4 (3.2)		12.2 (3.1)		9.1 (3.5)		10.3 (2.7)
Retaliatory supervision ^{*,‡}		6.9 (2.0)		6.7 (1.6)		6.3 (2.2)		7.3 (2.0)
Inability to communicate [†]	25 (21.0)		5 (19.2)		6 (17.1)		14 (24.1)	
Safety climate ^{***,‡}		23.0 (5.3)		24.3 (4.8)		19.9 (5.6)		24.3 (4.7)

* $P < 0.05$.

** $P < 0.01$.

*** $P < 0.001$ (two-tailed).

[†] P -values obtained using a Chi-square test.

[‡] P -values obtained using a one-way ANOVA across worker type groups.

Several indicators of work organization differed by construction trade (Table II). In terms of job structure, long work hours were reported least frequently by roofers and most frequently by framers. Precarious employment did not differ by trade. Turning to indicators of job design, skill variety, and control were lowest among roofers and highest among general construction workers. Psychological demand was higher among general construction laborers, but differences were not statistically significant. Perceived hazards were highest among roofers and lowest among framers. In terms of supervisory practices, framers had the strongest beliefs of their supervisors' ability to influence their job opportunities, while general construction laborers had the strongest beliefs that supervisors would engage in retaliatory practices on the job site. There were no differences by trade in difficulties communicating with supervisors. Appraisals of the safety climate were poorest among roofers relative to frames and general construction workers.

TABLE III. Work Organization and its Implications for Work-Related Injury Reported 3 Months Later Among Latino Residential Construction Workers Western NC (N = 107)

	OR (95% CI)	
	Simple ^a	Adjusted ^b
Job structure		
Long work hours (Yes vs. No)	1.52 (0.51, 4.56)	1.46 (0.39, 5.43)
Precarious (Yes vs. No)	0.81 (0.29, 2.27)	1.12 (0.36, 3.52)
Job design		
Skill variety	1.01 (0.84, 1.22)	1.09 (0.87, 1.36)
Control	1.00 (0.88, 1.13)	1.07 (0.93, 1.24)
Psychological demand	1.01 (0.88, 1.16)	1.04 (1.00, 1.22)
Hazards	1.10 (1.00, 1.21)	1.12 (1.00, 1.25)
Supervisory practices		
Powerful influence	0.98 (0.85, 1.13)	0.99 (0.84, 1.17)
Retaliatory supervision	0.90 (0.72, 1.12)	0.96 (0.75, 1.22)
Inability to communicate (Yes vs. No)	0.53 (0.16, 1.71)	0.56 (0.16, 1.93)
Safety climate	0.95 (0.88, 1.03)	0.97 (0.88, 1.07)

^aBivariate model with no adjustment.

^bModel adjusts for worker type (framing, roofing, vs. general construction labor) and amount of time spent performing construction work between baseline and 3 month follow-up interviews.

Simple bivariate analyses indicated little evidence that work organization factors were associated with injury risk (Table III). Greater perceived exposure to hazards was associated with greater injury risk (OR = 1.10). After adjustment for worker type and variation in total hours working in construction during the observation period, two work organization factors were associated with greater injury risk. For every unit increase in psychological demand the odds of experiencing an injury increased by 4%. Similarly, for every unit increase in perceived hazards the odds of experiencing an injury increased by 12%.

Paper #3, Discussion

The goal of this study is to enhance understanding of burden of occupational injury and the work organization factors underlying non-fatal injury among immigrant Latino residential construction workers. The burden of non-fatal occupational injury is likely higher than that suggested by official statistics [Dong et al., 2011], and a specific study of immigrant Latinos' experiences of work organization has the potential to inform why Latino

construction workers experience greater fatalities, injury, and illness [Dong and Platner, 2004; Dong et al., 2010]. Several strands of evidence from this study suggest that work organization poses threats to immigrant Latino worker health and safety. Injury rates in this sample were substantial and elevated in contrast to previous reports. The estimated incidence of work-related injury observed in this sample over a 3-month period was 55/100 FTE (95% CI . 41.4–71.6); a rate that is over 10-fold greater than the published annual injury incidence in construction (i.e., 4.2 injuries per 100 workers [BLS, 2010]). Dong et al. [2010] reported annual rates of 100–150 injuries involving time away from work per 10,000 (1.0–1.5 per 100) Latino workers between 2002 and 2008.

Although it is widely accepted that injury rates among construction workers are likely underestimated, especially among immigrant workers [Dong et al., 2011], the scope of underestimation remains unclear. Despite the imprecision due to the small sample, our data suggest substantially higher injury prevalence than reported in previous research. If estimates are limited to “major” injuries such as broken or fractured bones, dislocations and burns only, the observed injury incidence during the 3-month observation period was 15.7/100 FTE (95% CI . 3.4–15.8): a nearly fourfold increase over published annual rates. If estimates are limited to injuries involving time away from work, our data suggest a nearly threefold increase over published annual rates. Although direct comparisons with official BLS statistics cannot be made because of differences in data collection and measurement strategies, the results from this prospective study of immigrant Latino residential construction workers suggest previous attempts to quantify injury under-reporting may not have captured the full and potentially substantial scope of the under-reporting problem [Glazner et al., 1998; Dong et al., 2011]. Indeed, although imprecise, our estimates actually under-estimate injury prevalence because official BLS statistics do not include self-employed individuals, but two of the observed injuries were sustained by individuals who reported being a contractor or subcontractor.

A unique contribution of this study is the description of several work organization factors among Latino residential construction workers. Although there are few comparative data, the overall pattern of results from this study is that the organization of construction work is potentially risky: there are few points of overt problems, but there are also no points to suggest construction jobs occupied by immigrant Latinos are designed to protect, much less promote, worker health. For example, over 20% of workers in this sample

typically worked 45 or more hours per week, and over one-quarter of the sample (27.1%) were classified as having “precarious” employment, both of which have been linked to poor occupational health outcomes [Quinlan et al., 2001; Goldenhar et al., 2003; Dong, 2005], although only long work hours has been examined in the context of construction. On the more positive side, average “variety” scores were above the midpoint of the possible range of scores suggesting that Latino construction workers are engaging in a relatively diverse set of work-related activities and are avoiding repetitive and potentially monotonous tasks. Further, several variables reflecting both job design (e.g., “psychological demand” and “hazards”) and supervisory practices (e.g., powerful influence, retaliatory supervision, safety climate) had average scores located at the midpoint of the possible range. Thus, while there were few areas with clear problems, there was also substantial room for improvement.

The organization of construction work systematically differs across the trades. In terms of job design characteristics, roofers reported the lowest skill variety, the lowest level of control, and the highest exposure to hazards among the trades studied. Roofers also reported the lowest average safety climate scores. However, roofers were less involved in long work hours, and they reported more favorable supervisory practices, including the lowest average powerful influence and retaliatory supervision scores. Nevertheless, consistent with previous research [Dong et al., 2010], injuries were elevated among Latino roofers relative to Latino framers or general construction laborers. Although there was little evidence in this small sample that work organization factors robustly predicted injury, the differential exposure of roofers relative to framers and general construction workers to several job design features believed to undermine worker health and safety may play a role in their elevated incidence of injury [Dong et al., 2010]. This is a ripe area for future research, especially given the suggestive evidence that greater psychological demands and perceived hazards may increase injury risk.

The contributions of this study must be considered in light of its limitations. First, the generalizability of study findings is unknown because the sample was small, regional, and recruited using non-probability methods. Next, the incidence of work injuries involving time away from work should be interpreted with caution because the measure used to capture work-loss time did not differentiate whether the amount of time before returning to work rested solely on the injury, the day of the week the injury occurred, or the absence of work. If a worker who typically works Monday through Friday experienced an injury on Friday, and reported not returning to work until the second day after the injury (or later), it is possible that there was no lost work time. Direct comparisons between official BLS injury rates and our data should be made cautiously because of differences in how data are collected and how “injury” is measured. This broader study from which these data were obtained was not designed or powered to study the effects of work organization on injury; consequently, null associations should be interpreted with caution. Our analyses assumed a linear association between work organization attributes and risk of injury: readers and future researchers should consider the possibility of nonlinear associations. Further, the absence of objective measures of work exposures may confound associations of work organization with injury. Finally, there was no non-Latino comparison group so it is not clear if the experiences observed in this study are specific to Latinos in residential construction, or whether they reflect experiences of workers in this subsector more broadly. Future comparative research is needed to determine if the experiences of Latino workers in the subsector differ from other workers in the subsector.

Limitations notwithstanding, this study also has several strengths, and it makes several contributions to the construction safety and health literature. A key strength is the prospective design of the study with the relatively short look-back period for reporting injury incidence, which offers insight into the relative magnitude of injury underreporting among immigrant Latino workers. This is one of the first studies to describe the organization of construction work as it is experienced by immigrant Latinos. Although there were few glaring problems, it was also imminently clear that there is room for improvement. Latino residential construction workers have little variety in their jobs, little control over their work arrangements, and the safety climate on most construction sites is (at best) moderate. Collectively, the results suggest that work organization may contribute to elevated rates of non-fatal occupational injury among immigrant Latino residential construction workers. Although more research using a larger sample selected with probability sampling methods is needed, improving work

organization may help reduce occupational health disparities experienced by immigrant workers.

Paper #3, References

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Paper #4. Employer Provision of Personal Protective Equipment to Latino Workers in North Carolina Residential Construction

Paper #4, Background

Construction is among the riskiest occupations. In 2010 the fatality rate for construction workers was 9.5/100,000 full-time workers as opposed to 3.5/100,000 workers across all occupational sectors [1]. Four out of every 100 full-time construction workers sustain an injury each year, while 150 per 10,000 full-time-equivalent workers experience a work-related injury or illness requiring time away from work [2]. Construction is consistently among the top five sectors in terms of injury, illness and fatality statistics. Workplace health and safety is a particular concern for immigrant Latino workers, both because there has been a substantial increase in the proportion of Latino workers in the construction industry recently [3], and because they experience an increased risk for occupational fatality and injury [4, 5]. Further, immigrant workers in the United States and around the world are believed to have substantial difficulty accessing occupational safety and health rights and entitlements [6, 7]. Appropriate and regular use of personal protection equipment (PPE) is an important strategy for reducing elevated occupational injury and illness incidence in the construction industry [8]. The Occupational Safety and Health Administration (OSHA) requires employers to reduce or eliminate hazards; however, the total elimination of hazards is challenging because of the transient nature of projects, overlapping activities, and lack of innovation in construction equipment. Consequently, although it was intended as a tertiary strategy in occupational safety, PPE is oftentimes used by construction contractors as a primary strategy. Nevertheless, consistent use of PPE contributes to better occupational health outcomes. Chi and colleagues' [9] meta-analytic results suggest that improper use of PPE is a significant predictor of falls through floor openings and from building girders.

The presumptive value of PPE in protecting worker health is codified in the Code of Federal Regulations, which states: Protective equipment, including personal protective equipment for eyes, face, head, and extremities, protective clothing, respiratory devices, and protective shields and barriers, shall be provided, used, and maintained in a sanitary and reliable condition wherever it is necessary by reason of hazards of processes or environment, chemical hazards, radiological hazards, or mechanical irritants encountered in a manner capable of causing injury or impairment in the function of any part of the body through absorption, inhalation or physical contact [10]. Further, the regulation states that,

“the protective equipment, including personal protective equipment (PPE), used to comply with this part, shall be provided by the employer at no cost to employees” [11]. There are exceptions and exemptions to this standard; for example, employers do not have to pay for non-specialty footwear, like steel-toed boots, provided the employer allows workers to wear the boots outside of work [12]. Similarly, employers are not expected to pay for everyday clothing (e.g., long-sleeved shirts) or ordinary items (e.g., hats, sunglasses).”

Construction employers' compliance with this federal regulation, particularly in the small-scale residential sector, is unknown. Cattledge and colleagues [13] studied injuries among construction workers who did not use PPE and report that PPE frequently was not supplied, or that available equipment was inappropriate to the task or conditions. These findings parallel those from studies outside the construction industry. Whalley and colleagues' [14] study of farmworkers documented substantial deviation in compliance by farm owners and operators from OSHA's field sanitation standards and the Environmental Protection Agency's Worker Protection Standard. Although very little research has documented compliance rates with OSHA's requirement that employers provide employees with PPE without cost, available evidence suggests that employers, particularly small operators, are not following federal standards requiring employers to provide workers with basic PPE. Even less is known about the provision and use of PPE by immigrant Latino construction workers. No data could be located describing whether Latino construction workers receive no-cost PPE from their

employer. Nissen's [15] unpublished data suggest that Latino construction workers in medium- to large-scale construction enterprises are provided appropriate PPE without cost. They found that 98.6 percent of Latino construction workers in Florida who were employed on medium to large construction projects reported regular use of work boots, 89.7 percent reported regular use of protective eyewear, and 70.6 percent reported regular use of work gloves. Such high rates of regular use of these basic forms of PPE, to the extent these self-reported data are valid, suggest that employers are providing PPE without cost to employees. However there are no publicly available data on provision and use of PPE by immigrant Latinos in small-scale residential construction, perhaps the riskiest segment of the construction industry [16]. Using data obtained from a community-based sample of immigrant Latino workers employed in the residential construction industry in western North Carolina, this paper seeks to narrow current gaps in knowledge by describing the employer provision of PPE to immigrant Latino construction workers, documenting sources of variation in the receipt of employer-paid PPE, and delineating associations of employer-paid PPE with workers' regular use of PPE.

Paper #4, Methods and Materials

The data for this study are from a broader project designed to determine the feasibility of using interactive voice response (IVR) technology to collect daily diary data from Latino residential construction workers. The original project involved several distinct data collection components, including a baseline interviewer-administered survey, a 21-day daily diary protocol wherein participants used a personal telephone to access an IVR program that elicited structured information about work experiences and health, and an interviewer-administered follow-up interview three months after completing the baseline. This paper uses cross-sectional data from the baseline interviews.

Sample. Data were obtained from a non-probability sample of residential construction workers who self-identified as Latino ($N = 119$). Participants were recruited in partnership with Hogar Latino (HOLA) of Wilkes County, a nonprofit organization that serves the Latino communities of Wilkes and surrounding counties in western North Carolina. HOLA staff recruited residential construction workers through a combination of techniques including known individuals within existing social networks, referral to others by enrolled participants (i.e., snowball recruitment), and referral by individuals outside the study. Eligible interviewers were identified across several counties of western North Carolina, a region of the country characterized as a "new settlement community" because of the sharp increase in Latino population since 1990 [17]. Persons included as participants were 18 years or older, Latino (self or parents born in a Latin American country, or self-identified as "Latino" or "Hispanic") and currently employed in construction full-time, which we defined as having worked 35 or more hours per week in construction during the past two weeks. There were no exclusion criteria or special considerations that precluded an individual from participating in the study, despite meeting inclusion criteria.

Data Collection. Data were collected using interviewer-administered survey questionnaires between September and November 2010. The questionnaire assessed stable attributes of the individual (e.g., age, gender, country of origin), occupational characteristics (e.g., primary tasks performed in construction), health history (e.g., presence of chronic conditions), multiple indicators of the organization of work (e.g., work control, psychological demands), as well as provision and use of several forms of PPE. The questionnaire took an average of 48 minutes to complete, and participants received a \$15 incentive. All participants provided signed informed consent before any data was collected. Most interviews occurred in participants' homes. All recruitment and data collection activities were approved by the Wake Forest School of Medicine Institutional Review Board (FWA #00001435).

Questionnaire content was obtained from validated Spanish-language instruments without modification when available. English-only instruments and items developed for this project were translated into Spanish by a native Spanish-speaker. All items were then back-translated into English. Discrepancies identified in the back-translation were corrected through consensus and incorporated into both the Spanish and English versions of questionnaires [18].

Survey questionnaire data were collected by four trained interviewers. All interviewers were native Spanish-speakers. Training consisted of a thorough review of study purpose, screening and recruitment procedures, line-by-line review of the interviewer administered questionnaires, and progressively more realistic practice interviews.

Measures. Variables reflecting different aspects of PPE were constructed from self-reported responses to questions asked during the interviewer-administered questionnaire. Separate questions were asked as to whether the participant's employer provided eight specific types of PPE: eye protection (e.g., safety goggles, safety glasses or face shields), hearing protection (e.g., ear plugs, ear muffs), respiratory protection (e.g., dust masks or respirators), hand protection (e.g., non-slip gloves, heat/flame resistant gloves), special footwear (e.g., non-slip shoes, steel-toed footwear), head protection (e.g., hard hat), specialized hand tools (e.g., tools with soft or slip-resistant handles), and specialized material-handling tools (e.g., hand dollies). After each of the eight questions was asked, interviewers followed up each "yes" response by asking, "You indicated that your employer provided you {INSERT TYPE OF PPE}. Does your employer provide this without cost to you?" Participants who responded "no" to the question about the provision of PPE without cost were not probed further, so it is unknown if the employer charged employees for the PPE or if there was some other type of cost associated with receipt of PPE (e.g., intimidation, obligation).

One categorical variable was created for each type of PPE, and individuals were classified into one of three mutually exclusive categories based on their responses to the PPE questions. "Not provided" is the category representing participants who reported the employer did not provide the specific PPE. The "provided at employee cost" category represents a "yes" response to the question about whether the employer provided the PPE, but a "no" response to the probe as to whether the PPE was provided without cost to the employee. "Provided at no employee cost" represents participants who reported their employer provided the specific type of PPE, and it was provided by the employer without cost.

The necessity of various types of personal protective equipment is subject to substantial interpretation. We therefore organized the types of PPE into two major categories: "Basic" and "Exposure-Specific." Based on the presumption that use of safety glasses, hearing protection, hard-soled shoes or boots, and hard hats are basic for performing the vast majority of jobs on a construction site [19], we classified these types of PPE as "Basic," whereas the remainder were classified as "Exposure-Specific."

Use of PPE was assessed with a separate set of questions. To avoid responses that the worker felt were socially desirable, interviewers acknowledged to workers that use of PPE was highly variable. Specifically, interviewers were instructed to say, "Workers sometimes tell us that they do not use protective equipment, even when it is available to them. Sometimes workers don't use protective equipment because it is uncomfortable, it makes the work harder, or they simply prefer not to use it." Once this statement was made, the interviewer proceeded to ask "How often do you use [type of PPE]?" for each of the eight types of PPE. Response options used a frequency-based response set that ranged from 1 ("none of the time") to 4 ("all of the time"). A dichotomous "regular use" variable was created for each type of PPE: individuals who reported "most of the time" or "all of the time" were coded one for regular use, other responses (i.e., "none of the time" and "some of the time") were coded zero, reflecting non-regular use.

Age was measured in years and categorized to create similar age bands while ensuring adequate cell size in age category (i.e., < 28 years, 29-38 years, and > 39 years), and educational attainment was assessed based upon the grading system used in Latin American countries (i.e., Primary, Secondary, Preparatory, and University) and categorized into "Primary or less," "Secondary," and "Preparatory or higher." Country of origin was obtained and classified as either "Mexico" or "Other." Years in the United States was assessed and categorized into < 7 years, 8-15 years, and > 16 years. Participants were classified into one of three construction trades: framers, roofers, or general construction. Individuals were classified as being a framer if they were usually involved in building or assembling floors, walls, or roofs using lumber or light gauge metal framing at least three days per week. Participants were classified as roofers if they were usually involved in applying roof shingles, removing existing roof shingles, applying hot roofing tar or built up roofing, or carrying

roofing materials onto a roof at least three days per week. Individuals who self-identified as being a general construction worker and did not meet the definition of “framer” or “roofer” were classified as being a general construction worker. Precarious employment was measured with a single question asking “which statement best describes your work arrangement in construction” with three response options: “I am a construction contractor or subcontractor and do trades work myself,” “I have worked for the same contractor or subcontractor for three months or longer,” and “I have worked for several contractors or subcontractors during the past three months.” Individuals who reported working for several individuals in the past three months were coded one for precarious employment; all others were coded zero. Finally, participants were asked if they had ever completed an apprenticeship in any construction trade.

Analysis. Descriptive statistics are reported as frequencies and percentages for categorical variables. Due to the small cell sizes created by cross-classification necessary for making comparisons, Fisher’s Exact Tests were carried out in order to investigate differences in no-cost provision of PPE by personal characteristics. Likewise, Fisher’s Exact Tests were used to examine differences in regular use of PPE by no-cost, employer provision of PPE. All descriptive statistics and analyses were generated using SPSS v19.0.

Paper #4, Results

Nearly half the participants (47.1%) were aged 29-38 (Table 1); on average, they were 31.7 years of age (SD = 7.6). Most had little formal education; over one-third (n = 44) reported a primary education or less (equivalent to 6th grade in the United States) while nearly half (n = 50) reported having up to a secondary education (equivalent to 9th grade in the United States). Most participants (76.5%) reported being from Mexico, but nearly one-quarter of the sample was from Central American countries (primarily Honduras and Guatemala). Nearly one-half of participants (48.7%) reported being in the United States

Table 1. Personal and Occupational Characteristics of the Sample of 119 Individuals

	N (%) ^a		N (%) ^a
Age		Years in the United States	
≤ 28 years	42 (35%)	≤ 7 years	44 (37%)
29-38	56 (47%)	8-15 years	58 (49%)
≥ 39 years	21 (18%)	≥ 16 years	17 (14%)
		Construction trade	
Educational attainment		Framer	26 (22%)
Primary or less	44 (37%)	Roofer	35 (29%)
Secondary	50 (42%)	General labor	58 (49%)
Preparatory or more	25 (21%)		
		Precarious employment	
Country of origin		No	88 (74%)
Mexico	91 (77%)	Yes	31 (26%)
Other	28 (24%)		
		Apprenticeship ^b	
		No	91 (77%)
		Yes	26 (22%)

^aPercents may not sum to 100 because of rounding.

^bTwo missing cases.

Nearly one-half of the sample (n = 58) was classified as a general construction laborer, while less than one-third (n = 35) was classified as roofers and the remainder as framers. Over one-fourth of the sample (n = 31) was classified as having precarious employment. Approximately one-fifth of the sample (n = 26) reported having completed an apprenticeship. The type of apprenticeship completed by participants is not known, but was likely completed in another state prior to coming to North Carolina.

A substantial percentage of workers reported that PPE was not provided by their employer (Table 2). Looking

first at “basic” forms of PPE, one-third of workers reported their employer did not provide eye protection, and two-thirds said their employer did not provide hearing protection. Nearly four in ten workers said their employer did not provide hand protection, and over half reported their employer did not provide footwear. Over one-third of the sample said their employer did not provide head protection. Turning to “exposure specific” forms of PPE, approximately one-half of workers reported their employer did not provide respiratory protection. Over one-quarter of workers reported their employer did not provide specialized hand tools, and 38 percent reported their employer did not provide specialized material handling tools. Table 2 provides two perspectives on the provision of PPE without cost to workers. First, it provides a population perspective where the basis of comparison is the entire sample. From this perspective, employers infrequently provided no-cost PPE to

workers, and when it was provided without cost, it was commonly “exposure-specific” PPE. Over half the sample reported that their employer provided specialized hand tools and material handling devices without cost to workers (see “%a ” column under “Provided at no employee cost”). Half the workers reported that employers provided no-cost eye protection; otherwise, less than half the sample reported that their employer provided each of the other types of PPE at no cost. The most serious violation of the no-cost rule was in footwear: only 8 percent of workers reported their employer provided this PPE without cost.

The second perspective reflects the conditional provision of PPE; that is, if PPE was provided to workers, how frequently was it paid for by the employer? In this perspective, the denominator used to calculate percentages was the number of workers who reported having the specific type of PPE provided by their employer. When PPE was provided by the employer, in all but two types (hand protection, foot protection), 70 percent or more of workers said the PPE was provided at no cost (see far right column of Table 2). The three central columns of Table 2 report the small but non-negligible number of workers who were provided PPE by their employer but with cost to the worker. Again, the most serious violation of the no-cost rule was in footwear: 83 percent of those who said their employer provided footwear (36% of the total sample) reported the provided PPE had a cost to the worker. Otherwise, about one-third or less of employees who said their employer provided other types of PPE reported having a personal cost associated with that PPE

Table 2. Prevalence of Employer-Provided Personal Protective Equipment (PPE) by Type of PPE

	Not provided	Provided at employee cost		Provided at no employee cost	
	N (% ^a)	N	% ^a	N	% ^b
Basic personal protective equipment					
Eye protection (e.g., safety goggles, safety glasses, or face shields)	39 (3%)	21	18%	59	50%
Hearing protection (e.g., ear plugs or ear muffs)	78 (66%)	7	6%	34	29%
Hand protection (e.g., non-slip gloves, insulated gloves, or heat flame-resistant gloves)	46 (39%)	25	21%	48	40%
Special footwear (e.g., non-slip shoes, steel-toed footwear) [2 missing cases]	65 (55%)	43	36%	9	8%
Head protection (e.g., hard hats, plastic helmets, colored hats, or helmets with lamps)	45 (38%)	22	19%	52	44%
Exposure-specific personal protective equipment					
Respiratory protection (e.g., dust masks or respirators) [1 missing case]	63 (53%)	9	8%	46	39%
Specialized hand tools to avoid awkward postures and painful motions (e.g., tools with soft, slip-resistant, or anti-vibration handles) [1 missing case]	34 (29%)	7	6%	77	65%
Specialized material handling tools to make it easier to move heavy loads (e.g., hand dollies, boxes or crates with handles)	45 (38%)	5	4%	69	58%

^aDenominator is total sample (N = 119), unless there is missing data as noted in table in square brackets.

^bDenominator is number of individuals reporting the PPE is provided by the employer (119 minus number reporting not provided).

Table 3. Receipt of Selected No-Cost, Employer-Provided Personal Protective Equipment by Personal Characteristics

	Eye N (%)	Hearing N (%)	Hand N (%)	Foot N (%)	Head N (%)
Age					
≤ 28 years	15 (36%) ^a	6 (14%) ^b	11 (26%) ^b	3 (7%)	14 (33%) ^a
29-38	31 (55%)	18 (32%)	23 (41%)	6 (11%)	25 (45%)
≥ 39 years	13 (62%)	10 (48%)	14 (67%)	0 (0%)	13 (62%)
Educational attainment					
Primary or less	20 (46%)	14 (32%)	19 (43%)	3 (7%)	19 (43%)
Secondary	26 (52%)	10 (20%)	17 (34%)	3 (6%)	19 (38%)
Preparatory or more	13 (52%)	10 (40%)	12 (48%)	3 (13%)	14 (56%)
Country of origin					
Mexico	43 (47%)	23 (25%)	33 (36%) ^a	8 (89%)	35 (39%) ^b
Other	16 (57%)	11 (40%)	15 (54%)	1 (4%)	17 (61%)
Years in the United States					
≤ 7 years	14 (32%) ^c	4 (9%) ^c	13 (30%)	2 (5%)	12 (27%) ^b
8-15 years	36 (62%)	23 (40%)	26 (45%)	5 (9%)	32 (55%)
≥ 16 years	9 (53%)	7 (41%)	9 (53%)	2 (12%)	8 (47%)

^aDistribution differs ($p < 0.10$) based on Fisher's Exact Tests.

^bDistribution differs ($p < 0.05$) based on Fisher's Exact Tests.

^cDistribution differs ($p < 0.01$) based on Fisher's Exact Tests.

Receipt of no-cost, employer-provided basic PPE differed by personal characteristics (Table 3). Several differences were associated with age: a lower percentage of workers aged 28 years or younger compared to older workers received no-cost, employer-provided eye ($p < 0.10$), hearing, or hand and head ($p < 0.10$) protection. Receipt of no-cost employer-provided basic PPE did not differ by worker educational attainment. Worker country of origin was associated with types of PPE; a lower percentage of workers from Mexico than those from Central America received no-cost hand ($p < 0.10$) and head protection. Years in the United States was associated with several forms of PPE: a lower percentage of recent immigrants (i.e., those in the United States less than seven years), compared to those who have been in the United States longer, received no-cost, employer-provided eye, hearing, and head protection.

Receipt of no-cost, employer-provided PPE was consistently associated with regular use of "basic" forms of PPE (Table 4). A greater proportion of workers who received hearing protection at no personal cost reported regularly using hearing protection relative to those whose employers did not provide hearing protection at no cost to workers (including workers reporting their employer did not provide hearing protection). Similar associations were observed for no-cost employer provision and regular use of hand protection, specialized footwear, and head protection. The odds ratios estimating the magnitude of these associations ranged from 1.4 to 11.5; however, the 95 percent confidence intervals of these estimates were wide given the small sample. It is also noteworthy that a substantial proportion of workers do not regularly use the hearing, hand, and head protection, despite the fact it is provided without cost by their employer.

Paper #4, Discussion

Increasing workers' regular use of PPE is an important, albeit last-resort strategy for reducing elevated rates of occupational injury, illness and fatality in the construction industry [8]. The regular use of PPE is particularly important for the growing immigrant Latino workforce because rates of injury, illness and fatality are elevated among Latino construction workers relative to non-Latino construction workers [3-5]. Recognizing that complete elimination of hazards is not possible on most construction projects for many reasons, OSHA requires employers to provide sanitary and reliable PPE without cost to workers wherever work-related activities are capable of causing injury or impairment [10].

This study makes several contributions to the construction safety literature. The results suggest generally poor compliance, by employers in residential construction, with OSHA regulations requiring employers to provide PPE to workers without cost, and these results are consistent with the belief that immigrants have difficulty accessing occupational safety and health rights and entitlements [6, 7]. Estimates from our sample indicate that, at most, 50 percent of workers received eye, hearing, and head protection from their employer without cost. Although there can be ambiguity over which forms of PPE are essential, safety glasses, hearing protection, hard-soled shoes or boots, and hard hats are basic for performing the vast majority of jobs on a construction site [19]. No parallel data could be located to which we could compare our results. However, Nissen [15] reported that 93 percent of immigrant Latino construction workers working on medium- to large-scale projects in Florida reported that their employer required the use of a harness at all times. If we assume that required harness use reported by Nissen's study participants was supported by an employer-provided harness, our estimates of employer-provided, no-cost PPE are substantially lower. However speculative, the lower rates of employer-

Table 4. Association of Employer-Provided Personal Protective Equipment (PPE) with Employees' Self-Reported Regular Use of PPE, by Type of PPE

Employer provides PPE without cost to worker	Self-reported regular use of PPE		p-Value	Odds ratio (95% CI)
	No N (%)	Yes N (%)		
Eye				
No	45 (75%)	15 (25%)	0.169	1.8 (0.8–3.9)
Yes	37 (63%)	22 (37%)		
Hearing				
No	85 (100%)	0 (0%)	0.000	1.4 (1.14–1.76)
Yes	24 (70%)	10 (29%)		
Hand				
No	56 (79%)	15 (21%)	0.000	4.1 (1.8–9.1)
Yes	23 (48%)	25 (52%)		
Foot				
No	63 (59%)	44 (41%)	0.000	11.5 (1.4–94.9)
Yes	1 (11%)	8 (89%)		
Head				
No	51 (76%)	16 (24%)	0.000	3.9 (1.8–8.5)
Yes	23 (45%)	28 (55%)		

provided no-cost PPE in this study, relative to Nissen's study of workers on medium to large construction projects, is consistent with the notion that data reporting and adherence to OSHA regulations are likely to be particularly problematic in small-scale residential construction [16].

Our results also contribute to the literature by documenting specific risk factors associated with a lack of employer provision of no-cost PPE. We found that younger construction workers (i.e., those under the age of 28), and those who have been in the United States for fewer than seven years were less

likely to receive no-cost employer-provided PPE than older workers and those who have been in

the United States for longer periods of time. Together, these results suggest that recent immigrants in the construction industry are at greatest risk for not receiving no-cost PPE from their employers. Directly comparable data in the construction workforce, again, could not be located; however, these results are consistent with Nissen's [15] results indicating a difference in worker access to Material Data Safety Sheets by length of time in the United States. It is also consistent with research among Latino farmworkers. Whalley and colleagues [14] reported that younger farmworkers and those who worked in agriculture for fewer than 8 years were more likely to experience potential violations to migrant housing violations. Similarly, Robinson and colleagues [20] reported that farmworkers without a temporary work permit (H2A visa) were more likely to be recent immigrants and more likely to report minimum wage violations by their employer. Collectively, our results and that of previous work suggest that, while all immigrants have difficulty accessing worker protections and entitlements [6, 7], the challenge may be especially high for recent immigrants.

Latino construction workers' regular use of PPE might be increased if employers provided that equipment without cost to workers. Our results indicated that no-cost employer provision of hearing, hand, foot and head protection was associated with regular use of those forms of PPE. These associations need to be interpreted cautiously because of imprecision due to the small sample, and the fact that a substantial proportion of workers did not use PPE regularly despite having it provided at no cost by their employer. Nevertheless, our findings reinforce the importance of having PPE available to workers to encourage its use, which may in turn contribute to reductions in occupational injury and illness.

Strong policy implications cannot be drawn from a single small, regional study. However, if our findings are replicated by more definitive research, they foreshadow several issues and implications for policy. The most apparent policy implication is the obvious need for greater enforcement of OSHA regulations requiring employers to provide no-cost PPE. Of course this is a challenging task in small-scale residential construction because many states do not require contractors to register or obtain licensure: this makes tracking and monitoring their activities extremely difficult. Therefore, an important step in better enforcement of the no-cost PPE regulations is the development and implementation in every state of a licensure standard, for all construction contractors who pay two or more workers, that effectively captures all individuals and businesses involved in small-scale residential construction. An important accompanying policy is the linking of specific construction projects with contractors and sub-contractors, perhaps at the stage of issuing building permits. Comparable licensure standards across states and linkages between construction projects and the contractors hired to implement projects would enable tracking and inspection of small-scale residential contractors' adherence to occupational safety regulations, and it would provide a potential tool for imposing sanctions on non-adherent contractors.

Another policy implication is consideration of possible incentives to contractors to provide workers with no-cost PPE. One strong possible incentive is the provision of tax credits for all expenses pertaining to the provision of PPE to workers, which could be used to directly offset contractors' tax burden. One final policy implication is the apparent need to inform immigrant workers of their right to expect and request no-cost PPE. The creation and dissemination of block grants to public health departments or immigrant-focused service organizations could be valuable for educating immigrant workers about the protections they are entitled to, and for creating a worker demand for PPE.

The contributions and policy implications of this study must be considered in light of its limitations. First, the generalizability of study findings is unknown because the sample was small, regional, and recruited using non-probability methods. The results of this study should therefore be viewed as tentative until they are replicated by research using a larger, more representative sample of workers. Next, since there was no non-Latino comparison group, it is not clear if the experiences observed in this study are specific to Latinos in residential construction, or whether they reflect experiences of workers in this subsector more broadly. Comparative research is needed to determine if there are ethnic differences in the provision of PPE by employers, and workers' use of PPE, in this subsector of residential construction. Finally, there are limitations to our measures of PPE. The self-reported nature of our measures of both receipt of PPE from the employer and actual use makes them subject to reporting bias.

It is possible that employers had PPE available to workers, but the participants did not know it was available. Additional research using samples of employers would provide an important complement to research conducted with workers to discern actual adherence to federal regulations surrounding the provision of no-cost PPE. Finally, our assessment of PPE is incomplete. Fall restraint equipment, such as harnesses with functional tethers and anchors was missing from the list of PPE that we questioned.

Limitations notwithstanding, the results of this study make an important contribution to the construction safety literature. Our results suggest that many residential construction contractors employing immigrant Latino workers do not comply with OSHA's regulations requiring employers to provide workers with PPE at no cost. Our results also provide suggestive evidence that recent immigrants are less likely to receive no-cost, employer-provided PPE, and that employer provision of no-cost PPE may promote more regular use by Latino construction workers. If corroborated by more definitive studies on the topic, our results suggest that greater enforcement of OSHA regulations mandating employers to provide no-cost PPE to all workers, the provision of tax credits to incentivize contractors to provide PPE to workers, and public health initiatives to inform immigrant workers of employers' obligation to provide PPE all may play a role in reducing the occupational health disparities borne by Latino construction workers.

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Program Director/Principal Investigator (Last, First, Middle):		Grzywacz, Joseph, G	
Inclusion Enrollment Report			
This report format should NOT be used for data collection from study participants.			
Study Title:		Micro-Processes of Latino Construction Worker Safety: Feasibility of Computer-Assisted Telephone Surveys	
Total Enrollment:	119	Protocol Number:	
Grant Number:	U60OH009761	Project ID: 647	
PART A. TOTAL ENROLLMENT REPORT: Number of Subjects Enrolled to Date (Cumulative) by Ethnicity and Race			
Ethnic Category	Females	Males	Sex/Gender Unknown or Not Reported
Hispanic or Latino	0	119	0
Not Hispanic or Latino	0	0	0
Unknown (individuals not reporting ethnicity)	0	0	0
Ethnic Category: Total of All Subjects*	0	119	0
Racial Categories			
American Indian/Alaska Native	0	0	0
Asian	0	0	0
Native Hawaiian or Other Pacific Islander	0	0	0
Black or African American	0	0	0
White	0	119	0
More Than One Race	0	0	0
Unknown or Not Reported	0	0	0
Racial Categories: Total of All Subjects*	0	119	0
PART B. HISPANIC ENROLLMENT REPORT: Number of Hispanics or Latinos Enrolled to Date (Cumulative)			
Racial Categories	Females	Males	Sex/Gender Unknown or Not Reported
American Indian or Alaska Native	0	0	0
Asian	0	0	0
Native Hawaiian or Other Pacific Islander	0	0	0
Black or African American	0	0	0
White	0	119	0
More Than One Race	0	0	0
Unknown or Not Reported	0	0	0
Racial Categories: Total of Hispanics or Latinos**	0	119	0
* These totals must agree. ** These totals must agree.			

Project Publications

Journal Papers

Grzywacz JG, Quandt SA, Marín A, Summers P, Lang W, Mills T, Evia C, Rushing J, Arcury TA: [2013] The feasibility of interactive voice response methods in health behavior research with immigrant Latinos. *American Journal of Health Behavior* 37:238-247.

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Grzywacz JG, Donadio K, Quandt SA, Marín A, Summers P, Lang W, Mills T, Evia C, Arcury TA: [2011] Occupational injury and work organization among immigrant Latino residential construction workers. **Proceedings** of CIB-W099, Prevention: Means to the End of Injuries, Illness and Fatalities Conference, International Council for Research and Innovation in Building and Construction. Washington, DC, August 2011.

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Final Report

**Project ID 648 - From Finger-Pointing to Lifesaving: A Supply Chain
Approach to Construction OSH**

Project period: 09/01/2009-01/31/2015

Grant Number: 5U60 OH009761 – Project ID: 648

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April 21, 2015

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Abbreviations

AU	Australia
CHPtD	Construction Hazard Prevention through Design
D/B	Design/Build
DBB	Design/Bid/Build
DfS	Design for Safety
HOC	Hierarchy of Controls
OSH	Occupational Safety and Health
PPE	Personal Protective Equipment
PtD	Prevention through Design
r2p	Research-to-Practice

Abstract

Project title: From finger-pointing to lifesaving: a supply chain approach to construction OSH

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This project involved an unprecedented international benchmarking framework with a subcontractor in a country whose construction safety record, as measured by fatalities per 100,000, is twice as good as the U.S. record. The project itself was an exemplar for collaboration in general, and international collaboration, in particular. The project generated extremely valuable r2p products, and 15 (and counting) publications. The specific aims were to:

1. Map, analyze, and model the sociotechnical roles, relationships, information flows, interactions, and interdependencies that occur during the lifecycle of construction projects and impact OSH outcomes during the construction stage. The analysis will include the collection of data from projects representative of different sectors of the construction industry (e.g., residential, commercial, and industrial and heavy engineering), as well as projects procured by different delivery mechanisms (e.g., design-bid-build, design and construct, accelerated, and project alliancing).
2. Measure and graphically map the similarity/difference between the OSH attitudes and occupants' understandings of different sociotechnical roles in the construction industry. The understanding generated by the analysis will identify the underlying mechanisms by which occupants of disparate professional and functional roles form judgments of OSH risk and make decisions and take actions based on these judgments.
3. Evaluate the impact of collaborative project delivery methods and procurement strategies on OSH performance through the development of shared mental models of OSH and the creation of a unity of purpose with regard to project/industry OSH outcomes.

In benchmarking (e.g. Kleiner, 1994), the objective is to identify best practices that can be adopted or adapted. For this project, we identify infrastructure, and other contextual factors that likely contribute to the US:AU disparity in safety performance. Using a matched case study approach, we investigate US versus AU projects relative to delivery system (i.e. design/bid/build, design/build, accelerated, collaborative) and sector (i.e. residential, commercial, industrial, heavy) in terms of roles and safety decision making. We also report on whether roles in the supply chain lead to differences in risk perception/hazard identification. Finally and most significantly, we have designed and developed several useful and usable r2p products.

SECTION 1. SUMMARY: SIGNIFICANT FINDINGS, TRANSLATION, OUTCOMES

In benchmarking (e.g. Kleiner, 1994), the objective is to identify best practices that can be adopted or adapted. For this project, we identify infrastructure, and other contextual factors that likely contribute to the US:AU disparity in safety performance. Using a matched case study approach, we investigate US versus AU projects relative to delivery system (i.e. design/bid/build, design/build, accelerated, collaborative) and sector (i.e. residential, commercial, industrial, heavy) in terms of roles and safety decision making. We also report on whether roles in the supply chain lead to differences in risk perception/hazard identification. Finally and most significantly, we have designed and developed several useful and usable r2p products.

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2. Measure and graphically map the similarity/difference between the OSH attitudes and occupants' understandings of different sociotechnical roles in the construction industry. The understanding generated by the analysis will identify the underlying mechanisms by which occupants of disparate professional and functional roles form judgments of OSH risk and make decisions and take actions based on these judgments.
3. Evaluate the impact of collaborative project delivery methods and procurement strategies on OSH performance through the development of shared mental models of OSH and the creation of a unity of purpose with regard to project/industry OSH outcomes.

Significant Findings

The average Hierarchy of Control score at case level was statistically different between the US and AU. AU had a significantly higher HOC score than US. This result suggests that the higher levels of the Hierarchy of Controls, which are more design-oriented, is attended to more, as compared to the US.

The percentage of hazards in a project that were addressed during pre-construction were statistically different between US and AU. AU addresses safety challenges in the pre-construction phase at a significantly different level than the US. Simply, hazard identification occurs earlier in the process in Australia than in the US and differences in safety performance result.

The results showed a positive, significant correlation when decisions on the response to a hazard are performed more often in the pre-construction stage for both data sets. Similar to the previous finding, this result validates the effectiveness when safety decisions are made upstream at the pre-construction stage. Additionally, the results showed a significant difference on Hierarchy of Control intervention when an activity is controlled during the pre-construction versus construction stage of a project.

The constructor or key subcontractor being involved in the pre-construction stage has a positive effect on safety (HOC). Regarding roles and the prescription to make safety decisions earlier, contractor and subcontractor involvement upstream positively affects performance. On a related note, the results indicated a positive effect of supplier engagement early in the procurement process as a strategy to improve social sustainability outcomes.

There is no absolute within-group homogeneity among professional groups nor are between-group differences always evident with respect to participants' OSH risk perceptions associated with the selected building systems/technologies. Simply, designers, constructors and others do not differ in their risk perceptions. This could actually be beneficial in upstream safety collaboration and decision making. For example, downstream constructors do not have a heightened sensitivity for safety that would need to be imparted upon designers for effective collaborations.

Translation of Findings

Aim 3 was focused on translating r2p deliverables. Several deliverables are attached to this report. Collectively, they translate the following into practice:

- AU is more advanced in implementing higher-level controls than US.
- At least addressing the hazard earlier can lead to more high-level controls.
- Decisions made during the design stage of a project can have a significant “downstream” impact upon OSH.
- The integration of process knowledge into product design decisions can significantly improve the quality of OSH risk control in construction
- Consideration of OSH early (in pre-construction stages of the project life-cycle) can be linked to implementing higher order controls for OSH risks during the construction stage
- OSH risk is subjective in nature and individual risk perception is the result of the interplay between these attributes

In addition, case studies were developed as part of Aim 1. These case studies have been shown to be quite useful as training tools.

Outcomes and Impact

This project involved an unprecedented international benchmarking framework with a subcontractor in a country whose construction safety record, as measured by fatalities per 100,000, is twice as good as the U.S. record. The project itself was an exemplar for collaboration in general, and international collaboration, in particular. The project generated extremely valuable r2p products, and more than 15 publications. It is also believed that this project broke new ground on the feasibility and effectiveness of international collaboration for improvements in the US Construction Industry. The project team overcame many obstacles at the outset. Today, benchmarking other countries who outperform the US in OSH is much more accepted.

Section 2. Scientific Report

Background

The construction industry performs relatively poorly in occupational safety and health (OSH). This is relative to other sectors as well as other countries. Despite advances in technology and the implementation of robust safety management systems, construction workers continue to suffer a persistent and intransigent incidence of work-related fatalities and costly injuries and illnesses. These incidents are preventable, most of them arising as a result of well-understood hazards, which can be controlled through the adoption of known risk elimination/reduction interventions and solutions. Thus far, the majority of OSH efforts in construction have been implemented at the level of the construction firm, although there is a growing recognition that the root causes of OSH incidents can be traced back to problems inherent in industry-level systems of work. For example, in one review of 100 incidents in the United Kingdom construction industry, researchers identified client requirements, design criteria, and the project procurement environment as contributing factors to incident occurrence. Thus, we hypothesized there would be value in focusing on roles in the supply chain of construction. We were correct.

The National Occupational Research Agenda (NORA) strategic plan has reported organizational and management goals associated with construction OSH, specifically, through Goals 8-15. In this regard, there is emerging evidence that to make further impacts and address the intransigent residual level of injury, illness, and death in construction, a systems, 'whole industry' approach is required. Despite calls for the engagement of owners/clients, designers, engineers and constructors and all contributors to construction projects in the OSH effort, high levels of technological, organizational, and cultural differentiation present a significant barrier to the integration of OSH into the currently fragmented construction supply chain. This subproject addressed this challenge in the context of NORA Goal 10, by identifying the way in which complexity associated with structures of work, information, and governance within construction projects (and by extension, the broader industry) impacts OSH performance during the construction stage; examining the extent to which differentiation in the construction industry supply chain impedes the development of a 'unity of purpose' with regard to OSH among strategic stakeholders; and evaluating the extent to which collaborative project delivery mechanisms and procurement methods support the integration and optimization of OSH hazard elimination/risk reduction throughout the project lifecycle.

Specific Aims

The proposal for this work included three aims for the research:

- AIM #1 – To map, analyze, and model the sociotechnical roles, relationships, information flows, interactions, and interdependencies that occur during the lifecycle of construction projects and impact OSH outcomes during the construction stage. The analysis will include the collection of data from projects representative of different sectors of the construction industry (e.g., residential, commercial, and industrial and heavy engineering), as well as projects procured by different delivery mechanisms (e.g., design-bid-build, design and construct, accelerated, and project alliancing).
- AIM #2 – To measure and graphically map the similarity/difference between the OSH attitudes and occupants' understandings of different sociotechnical roles in the construction industry. The understanding generated by the analysis will identify the

underlying mechanisms by which occupants of disparate professional and functional roles form judgments of OSH risk and make decisions and take actions based on these judgments.

- AIM #3 – To evaluate the impact of collaborative project delivery methods and procurement strategies on OSH performance through the development of shared mental models of OSH and the creation of a unity of purpose with regard to project/industry OSH outcomes.

This report addresses each of the three aims individually within each section of the report.

Report for Aim #1

The methodology for AIM #1 is divided into a description of the statistical analysis and Social Network Analysis (SNA).

Methods

Statistical analysis

The research adopted a comparative, matched case study approach. Data were collected from a total of 23 construction projects, 10 in Australia/New Zealand and 13 in the United States of America (USA). For each project, features of work were purposefully identified by project participants in consultation with the research team. Features of work were selected as the unit of analysis because they presented a particular health and safety problem or challenge.

For each feature of work, comprehensive data were collected to capture decisions that were made in relation to the design of the feature of work, the process by which it was to be constructed and the way that health and safety hazards were to be addressed. Data were collected by conducting in-depth interviews with stakeholders involved in the planning, design and construction of the selected features of work. During the course of the research 288 interviews were conducted (185 in Australia and 103 in the USA). The average number of interviews per feature of work was 6.7.

Dependent variable

Data were collected on OSH hazards and the risk control solutions implemented within the case examples. The data were elicited during interviews and supplemented with site-based observations and examination of project documentation (e.g. plans and drawings). For each feature of work, a score was generated reflecting the quality of implemented risk control solutions. This score was based on the hierarchy of controls (HOC).

An average HOC score was generated for each feature of work, reflecting the quality of risk control solutions implemented for identified OSH hazards/risks. Each level of the HOC was given a rating ranging from 1 (personal protective equipment) to 5 (elimination). The risk controls implemented for hazards/risks presented by each feature of work were assigned a score on this five-point scale. In the event that no risk controls were implemented, a value of zero was assigned. Using these values, the mean HOC score for each feature of work was

generated. Thus, if two hazards were identified, one was eliminated and the other controlled by administrative methods, the mean score would be 3.5.

Social Network Analysis (SNA)

SNA was utilized to explore and understand the communication process occurring in construction project networks. Initially interviews were conducted with key project participants, i.e. the client, the principal design consultant and the construction contractors. From these interviews, other actors (leads) in the network were identified. These 'leads' were followed up if certain criteria were met. This process of sampling continued until no new leads were identified in actors' interviews. Data were verified by confirming the existence of each network link with both actors. Thus, at least two actors had to confirm that a link between them existed for it to be included in the SNA. All participants were asked to rate the frequency of their communication during pre-construction and construction stages of the project. Each actor was asked two questions; 'How frequently did you give information to this person when [a particular decision] was being made?' and 'How frequently did you receive information from this person when [a particular decision] was being made?' Participants responded to these questions using a five-point Likert scale ranging from 1 (occasionally) to 5 (daily).

Independent variables

Two independent variables were measured - network density and the degree centrality of the constructor.

Dependent variable

The hierarchy of control (HOC) score was used as the dependent variable for this analysis.

Results

Statistical analysis results

The following results include findings from both the Australian and USA cases. Table 1 & 2 identifies the type of projects drawn from both countries and details 23 cases drawn from ten projects in Australia, and 20 cases from 13 projects in the USA. The Australian projects were drawn from all four sectors of the construction industry, and taken from a range of delivery/procurement mechanisms.

Table 1. Australian project matrix (23 cases from 10 projects)

Project	Country	Number of Interviews for each case	Case/Feature of work	Description
Centrifuge replacement for sewerage treatment facility	AUS	13	Installation of centrifuge	Removing 2 old centrifuges and installing one larger centrifuge to replace them
	AUS	13	Pipe works	Upgrading and installation of new pipes to connect the new centrifuge to the existing infrastructure
	AUS	9	Installation of a steel platform	Erection and installation of a steel platform over a void to provide access around the centrifuge for maintenance
Theatre demolition	AUS	8	Demolition	Demolition of a standalone lecture theatre to open up the area in preparation for future work
Public space landscaping	AUS	5	Landscaping	Landscaping an open square area using coloured artificial turf to create a geometric overlay
42-story residential Complex	AUS	6	Construction/installation of WRAP façade	Construction/installation of a self-supporting, architectural façade element with steel and RC members connected to the exterior of the building
	AUS	5	Construction of internal stair egress	Construction of a 'U' shape stair egress around the central building core with alternative landings between each floor to comply with fire regulations
Manufacturing facility	AUS	11	Roof and Wall Cladding	Installation of roof panels/sheets and skylights on roof structure, wall panels and openings
	AUS	8	Erecting/Installation of roof structure	Construction and installation of main spine trusses and trussed rafters for roof structure
	AUS	11	Erection/installation of steel columns	Erection/installation of four rows steel columns
	AUS	9	Construction of foundation system	Excavation and construction of pad foundations
Food processing plant reconstruction	AUS	8	Steel columns	Strengthening of the existing steel structure
	AUS	5	Sewerage disposal system	Installation of a new system for treatment/disposal of waste water with higher capacity and efficiency
	AUS	10	Fire wall	Construction of a fire wall as well as fire tunnels inside the production facility to comply with fire regulations
Cemetery mausoleum	AUS	8	Construction of basement mausoleum	Construction of basement mausoleum including excavation, temporary works, retaining walls, roof slab, finishing and mechanical works

Suburban train station	AUS	6	Construction of RC columns	Construction of RC columns supporting a pedestrian access bridge
	AUS	6	Construction of ramp access	Construction of a ramp accessing the platform
	AUS	6	Construction of platform and supporting columns	Construction of a concrete platform with steel frame and its supporting columns and foundation
Water pumping station upgrade	AUS	11	Construction of wet well	Construction and installation of an RC tank and pipework
	AUS	5	Construction of valve chamber	Construction of valve chamber including concrete walls and a base slab
Flood recovery works	AUS	8	Construction of a retaining wall on site 1	Data collection, clearing works, building access road on site 1 and construction of a gabion wall and its foundation
	AUS	8	Construction of a retaining wall on site 6	Data collection, clearing works, building access road on site 6 and construction of a gabion wall and its foundation
	AUS	6	Rectification of a pedestrian bridge	Installation of temporary works and elevation of a bridge deck over a creek

Total: 10 projects, 23 cases.

Table 2. United States of America project matrix (20 cases from 13 projects)

Project	Country	Number of Interviews for each case	Case/Feature of work	Description
Football stadium	USA	7	Foundation system	Excavation & Installation of micro-pile foundation system adjacent to existing parking garage and around existing utilities
	USA	8	Steel superstructure	Demolition of existing stands and steel erection of new seating structures and press box
Psychiatric hospital	USA	5	Exterior pre-cast concrete panels	Lift and place of pre-cast concrete panels on exterior and attachment to structural steel

	USA	6	Roof structure and barricades	Installation of roof membrane and construction of permanent roof barricades around HVAC
House construction	USA	2	Exterior structures (basement, exterior walls, roof)	Pre-fabrication and construction of exterior & interior walls and roof structure
Wastewater tank	USA	9	Pre-stressed concrete steel tank	Excavation and shoring of tank location and construction of pre-stressed concrete tank
	USA	9	Sewer trunk line across creek	Installation of sewer trunk line across creek from barge using divers
House construction	USA	3	Exterior structures (basement, exterior walls, roof)	Site excavation, installation of pre-formed concrete basement, and construction of exterior walls and roof structure
Server farm	USA	3	Demolition of existing structure	Demolition of existing one-story structure and separation of waste and recyclables for LEEDS
	USA	4	Gas fire suppression system	Installation of tanks, actuator valves, and distribution pipe for gas fire suppression system
College cafeteria	USA	5	Foundation system	Excavation of site and construction and backfill of front retaining wall
	USA	6	Steel superstructure	Delivery of steel beams and lift and place of steel structure around two adjacent buildings
Chemical plant upgrade	USA	5	Steel structure for new equipment	Pre-fabrication of steel structure for new equipment and tie-in to existing plant infrastructure
Road reconstruction	USA	6	Maintenance of traffic	Maintenance of traffic plan during reconstruction of 6-lane highway and repavement of adjacent side streets
	USA	6	Utility replacement	Excavation and condemnation of existing utilities and installation of new utilities
Bridge Reconstruction	USA	4	Maintenance of traffic	Maintenance of traffic during removal of existing asphalt and installation of new asphalt on one lane of 4-lane bridge
New Interstate	USA	6	Maintenance of traffic	Maintenance of traffic on haul roads, temporary bridges, and public roads
Hospital	USA	4	Steel superstructure	Lift and place of steel beams for structure
	USA	4	Internal systems	Pre-fabrication of internal walls and installation of electrical and mechanical systems in building
House	USA	1	Exterior structures (basement, exterior walls, roof)	Site excavation, installation of pre-formed concrete basement, and construction of exterior walls and roof structure

Total: 13 Projects, 20 cases.

The results show that the US has a mean HOC of 2.48 with 95% confidence interval of 2.33 – 2.62, while the AU has a mean HOC of 3.69 with a 95% confidence interval of 3.4 – 3.98 (see Figure 1). This shows that there is a statistical difference in the level of control of potential hazards between the data sets. Also interesting is that there is a 47% difference in lost time rates between the two countries (11.1 to 5.9) according to recent data, and there is a 49%

difference in the HOC score above (3.57 to 2.48). While we cannot make the assumption that controlling at a higher level is the sole cause for this discrepancy in performance, it is interesting that the differences are so close.

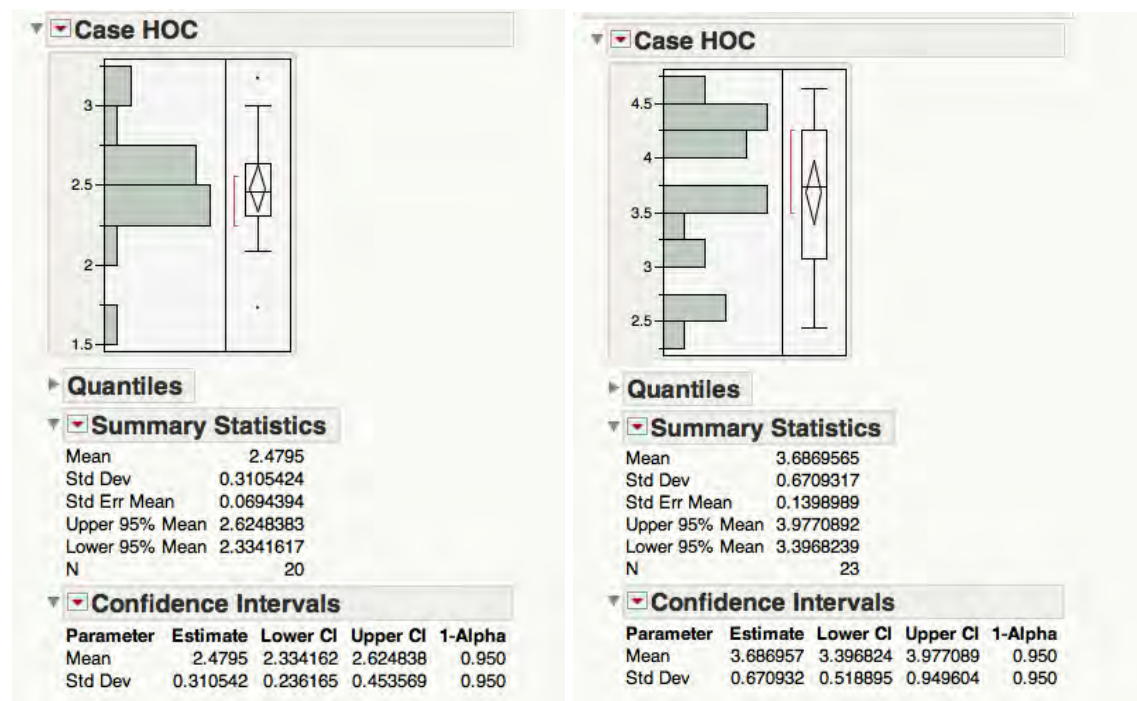


Figure 1. Case level HOC analysis results of US side (L) and AU side (R).

The Australian cases in the analysis had higher average HOC scores than were evident in the USA cases (Table 3). Furthermore, the difference between mean HOC scores of the USA and Australian cases was found to be statistically significant ($t=7.731$, $p=.0001$). Cases embedded within projects delivered using collaborative or design and build delivery methods had slightly higher HOC scores than cases embedded within projects delivered using an accelerated (fast track) or design-bid-build delivery approach. Cases embedded in commercial and residential construction projects had lower mean HOC scores than cases embedded in projects within the engineering and industrial construction sectors. However, the differences in HOC scores were not significantly different between cases embedded in projects using different delivery methods or in different industry sectors.

Table 3. Mean HOC scores by country, project delivery method and industry sector

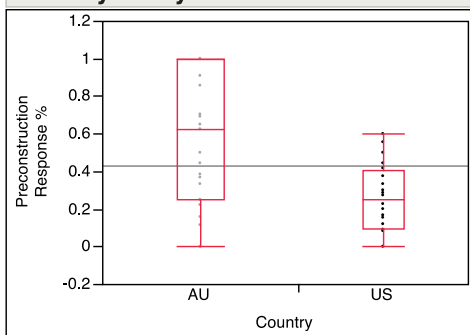
Case descriptor	Mean HOC score	Standard deviation
<i>Country</i>		
United States	2.48	0.311
Australia	3.69	0.671

<i>Delivery method</i>		
Collaborative	3.36	0.632
Accelerated	2.98	0.820
Design-bid-build	2.71	0.602
Design and Build	3.38	0.233
<i>Sector</i>		
Heavy engineering	3.33	0.844
Residential	3.02	0.777
Commercial	2.72	0.649
Industrial	3.13	.807

The total percent of safety challenges addressed during pre-construction for each case was calculated for the US and AU data. For the US data, the mean percentage of hazards addressed during pre-construction was 26% with a 95% confidence interval of 17%-34%. For the AU data, the mean percentage was 57% with a 95% confidence interval of 42%-73%. These confidence intervals do not overlap, which supports that hazards are addressed more often in pre-construction in Australia versus the US.

A normal goodness-of-fit test was performed on both sets, and there was evidence to reject the null hypothesis that the AU data for pre-construction response % is normal (goodness of fit p-value=0.0288). Therefore a nonparametric test was run to look for evidence of differences, and it also supports a difference in the percentage of hazards on a case that was addressed during pre-construction between the two countries.

Oneway Analysis of Preconstruction Response % By Country



Quantiles

Level	Minimum	10%	25%	Median	75%	90%	Maximum
AU	0	0.046	0.25	0.625	1	1	1
US	0	0	0.09825	0.25	0.4065	0.5504	0.6

Nonparametric Comparisons For All Pairs Using Steel-Dwass Method

q*		Alpha						
1.95996		0.05						
Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
US	AU	-11.2174	3.830648	-2.92833	0.0034*	-0.333000	-0.556000	-0.104000

Figure 2. Comparison of hazard control activities in preconstruction stage between US and AU.

The results show a positive, significant correlation when decisions on the response to a hazard are performed more often in the pre-construction stage for both data sets. This aggregates all of the activities on a given project into an overall percentage of the amount of time the safety challenges for a given activity are addressed in the pre-construction stage in order to get an overall analysis at the case level. While similar to the analysis below, in which each individual activity is analyzed, analysis is intended to put every case on the same level (regardless of number of observations/activities in that case) to see if addressing safety earlier tends to lead to more high level hazard controls. It is interesting that the correlation for the AU data is much stronger than the US data (0.6842 versus 0.4406). This speaks to the safety orientation of stakeholders in the AU, as well as possibly the trend to look at safety as a compliance issue in the US.

The results show a significant difference of the HOC when an activity is controlled during the pre-construction versus construction stage of a project. The mean response on the five-point HOC scoring system for hazards controlled during the pre-construction stage was 3.69 versus 2.13 for hazards addressed during the construction phase in the US data. For the AU data the mean response when addressed during construction was 2.92 versus 3.69 when addressed in the pre-construction stage. This supports that most of the time all that is left as a hazard control are PPE and administrative controls if left to the construction stage of a project. While every control during the pre-construction stage can obviously not be a higher-level control, the data support that at least addressing the hazard earlier can lead to more high-level controls.

The results indicate a positive effect of supplier engagement early in the procurement process as a strategy to improve social sustainability outcomes. When safety was a decision influence during the design and procurement stage (9 cases) there does appear to be a higher level of control for potential hazards per project. The data show that there is in fact a positive performance impact of early supplier involvement, Table 4 gives an overview of all twelve of these cases, and the primary reason attributed by interviewees for why the early engagement was initiated.

Table 4. Cases with early supplier engagement

Case	Type of Purchase	Reason for Early Supplier Involvement
Football Stadium Foundation System	Strategic	Proximity to adjacent structures made foundation important feature
Psychiatric Hospital Precast Panels	Leverage	Volume of panels on exterior
Psychiatric Hospital Roof Structure Barricades	Leverage	Volume of barricades
Wastewater Tank Prestressed Concrete Tank	Strategic	Construction of tank was key component of project

Server Farm Gas Fire Suppression System	Bottleneck	Few suppliers and specialized item
University Cafeteria Steel Superstructure	Strategic	Critical driver of project schedule and cost
Chemical Plant Steel Tower	Leverage	Coordination required to minimize construction time at plant
New Interstate Maintenance of Traffic	Leverage	Volume of interfaces with existing roadways
Hospital Steel Superstructure	Strategic	Critical driver of project schedule and cost
Hospital Interior Walls and Systems	Leverage	Volume of interior walls , mechanical, and electrical in building
Coal Plant Upgrade Utility Installation	Leverage	Volume of new utilities required to serve upgrade
Coal Plant Upgrade Duct System	Leverage	Volume of duct and associated supports required

Each decision influence was coded into one of ten categories in order to analyze the prevalence of different influences during the lifecycle of a project (see Table 5). For each feature of work, it can be analyzed as to whether a given influence was found to exist or not. The table below shows that decision influences such as effectiveness (meeting organizational or project level goals), quality, and funding are much more frequent during the earlier stage of a project versus safety. Multiple influences could be present during each stage, and this data set is just an overview of the types of influences guiding the decision-making process on construction projects over their lifecycle. For the AU data, safety was a decision influence in the pre-construction phases of a case 60.9% of the time, which is substantially higher than the US data.

Table 5. Decision Influence differences between stages

Decision Influence	Project Stage		
	Planning	Design & Procurement	Construction
1. Efficiency	27%	87%	67%
2. Effectiveness	87%	67%	27%
3. Productivity	0%	33%	73%
4. Quality	27%	80%	53%
5. OSH	13%	27%	93%
6. Innovation	0%	0%	0%
7. Funding	80%	87%	60%
8. Regulatory	20%	13%	60%
9. Policy	33%	40%	13%
10. Other Stakeholders	13%	7%	0%

Interestingly, when safety was a decision influence during the design stage (4 projects) there does appear to be a higher level of control. The average hierarchy of control score for these cases was 2.88 while the remaining 11 cases had an average score of 2.28. This is statistically significant with a p-value of 0.0438, and further supports the argument of safety being a decision influence earlier in the project lifecycle in a similar manner to other types of influences.

Social Network Analysis (SNA) results

To illustrate, the SNA reported was for Australian projects since the aforementioned results clearly present Australia as the benchmark, that is the country from which to adapt or adopt best practices. From a pool of 23 cases (across 10 projects) the SNA was applied to 13 cases. The following results describe three outcomes; quality of risk control, project network metrics and the relationship between project network characteristics and risk control outcomes.

Quality of risk control

The quality of OSH risk control solutions implemented was rated for all 23 cases in the analysis. The results of these ratings are presented in Table 3. The mean HOC score for all 23 cases was 3.69 (SD = 0.67). The maximum HOC score was 4.63 and the minimum was 2.44. These scores did not differ greatly from the 13 cases for which social network analysis data were available. The mean HOC score for the cases for which social network analysis data were collected was 3.84 (SD = 0.65). The maximum HOC score for cases for which social network data were collected was 4.63 and the minimum was 2.30.

Project network metrics

Table 6 presents descriptive statistics for the 13 cases for which complete social network data were available. The extent of the construction contractors' out-degree centrality varied considerably between cases. The average score was 11.33 (SD = 7.10). The frequency with which the construction contractor engaged in outward communication with other parties in the project network varied considerably. The average out-degree centrality score was 11.33 (SD = 7.10) in preconstruction project stages and 13.09 (SD = 6.62) for the entire project period. The average network density values were 0.27 (SD = 0.18) in pre-construction stages, and 0.61 (SD = 0.28) for the entire project period.

Relationship between project network characteristics and risk control outcomes

Table 7 shows the results of the comparison of mean social network values between cases with the highest and lowest HOC scores. Network density was higher in cases with more positive HOC outcomes. This was the case for overall project network density and network density measured only in the pre-construction (i.e. planning and design) stage of the project. However, the independent samples t-tests revealed that the difference in network density among cases with high compared to low HOC values was not statistically significant. Constructors' out-degree centrality was higher in cases with more positive HOC outcomes. This was the case for the constructor's degree centrality measured across the project as a whole, as well as the constructor's degree centrality relating to only the preconstruction (i.e. planning and design)

stage. In both cases, the independent samples t-tests revealed these differences to be statistically significant.

Table 6. Descriptive statistics for social network characteristics (N=13 cases)

	<i>N</i>	Minimum	Maximum	Mean	Std. Deviation
Pre-Construction Normalised Degree Centrality	13	1.76	24.81	11.33	7.10
Overall Normalised Degree Centrality	13	3.33	23.33	13.09	6.62
Pre-Construction Network Density	13	0.074	0.63	0.27	0.18
Overall Network Density (Whole Project)	13	0.119	0.61	0.28	0.15

Table 7. Comparison of cases with lower versus higher than average HOC scores

Variable	HOC grouping	Mean	T value	DF	Significance (<i>p</i>)
Project network density (pre-construction stage)	High HOC	0.268	-1.231	3.206	NS
	Low HOC	0.149			
Constructor's normalised degree centrality (pre-construction stage)	High HOC	14.193	-3.636	2.071	0.022
	Low HOC	5.377			
Project network density (whole project)	High HOC	0.168	-1.535	3.085	NS
	Low HOC	0.286			
Constructor's normalised degree centrality (whole project)	High HOC	16.080	-3.148	3.886	0.035
	Low HOC	9.103			

NB: Cases with High HOC scores are those for which $HOC > \text{mean} + 1 \text{ standard deviation}$, cases with low average HOC scores are those for which $HOC < \text{mean} - 1 \text{ standard deviation}$.

Discussion

Early consideration of OSH and risk control outcomes

Figure 3 shows the relationship between the extent to which health and safety risk controls were considered and decided upon before commencement of construction (i.e., in the planning or design stages of the project) and the quality of risk control outcomes (i.e., the average HOC score). Figure 3 shows a positive relationship between the consideration of health and safety in the early stages of a construction project and the eventual implementation of higher order (i.e., technological) risk controls in the construction stage. The relationship was also statistically significant ($r=.737$, $p=.0001$).

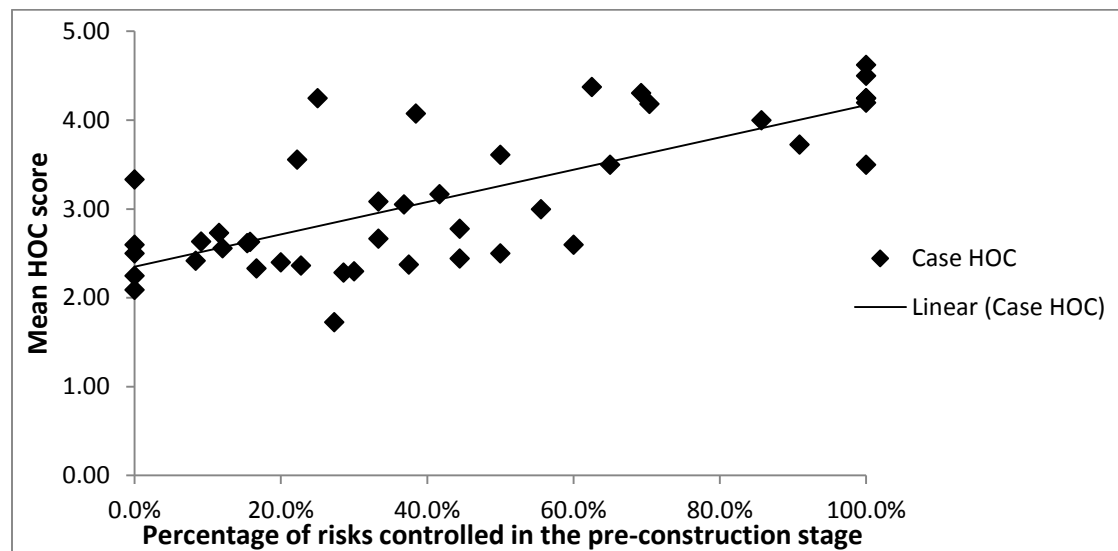


Figure 3. Linear relationship between the pre-construction OSH intervention the mean HOC score.

The importance of construction process knowledge

The research provides preliminary empirical evidence that the integration of construction process knowledge in design decision-making, as evidenced by information flowing from the construction contractor to other project participants, is linked to the adoption of more effective OSH risk control solutions.

The results (refer to Table 6, 7) revealed a significant difference in the constructors' degree centrality values between cases with above and below average HOC scores. These findings do not indicate a causal relationship, but do suggest that knowledge of construction processes is an important and valuable resource that can support the adoption of preferred technological controls for OSH risks. Compared to other project participants, construction contractors have a high level of construction expertise because of their specialized training and experience in the application of construction materials and methods. Constructors are arguably in the best position to provide advice about OSH hazards/risks and ways to mitigate them in construction activities. Construction contractors are also responsible for construction operations and have a strong motivation and interest in ensuring work can be performed with minimal risk to OSH.

Integrating mechanisms

The results highlight the potential OSH benefit by integrating construction process knowledge into the design of facilities. Unfortunately, the fragmented and sequential nature of design and construction work inherent in construction projects can mitigate against this integration. Integrated project delivery methods may increase the extent that process knowledge is used to inform product design in construction projects. However, the fact that no significant differences were found between the HOC scores for cases drawn from projects procured in different ways suggests that collaborative forms of project delivery do not guarantee better OSH outcomes. There is also potential to improve OSH outcomes through the adoption of concurrent engineering (CE). CE is characterized by a unified development process and a multidisciplinary project delivery team and has been proposed as a technique to improve construction productivity. Another key feature of CE is the concurrency or overlapping of activities. The integration of product and process design has been recommended as a means to improve construction project performance. The research results suggest that simultaneous consideration of product and process design could produce significant improvement in the quality of ways in which OSH risks are controlled.

Quality of risk control as a measure of OSH effectiveness

The research also developed a new method for measuring OSH performance in research. Commonly used measures (e.g. the frequency or rate of occurrence of accidents), are notoriously unreliable and lagging measures of safety performance in construction projects. Thus, using accident occurrence as a dependent variable in research is problematic. The use of the HOC provides a more direct, leading, and useful measure of the quality of OSH risk mitigation efforts and more directly measures the quality of OSH outcomes. Thus, we propose using the HOC as a valid “leading indicator” of OSH performance in future research.

Conclusion

The failure to address OSH in design is at odds with contemporary thinking in OSH risk management, in which the most effective means of dealing with a hazard is to eliminate it at source. There is compelling evidence to suggest that decisions made during the design stage of a project can have a significant “downstream” impact upon OSH. However, research suggests structural and practical impediments to the effective implementation of Prevention through Design (PtD) or Design for Safety (DfS) in construction projects. The research provides evidence that the integration of process knowledge into product design decisions can significantly improve the quality of OSH risk control in construction. It is recommended that project participants consciously adopt project delivery and management strategies that will support this integration. In addition, the research suggests that the provision, through curriculum change, of construction process knowledge to designers of the constructed product (i.e., engineers and architects) could also help to optimize OSH risk control outcomes.

The research also provides some evidence that consideration of OSH early (in pre-construction stages of the project life-cycle) can be linked to implementing higher order (preventative) controls for OSH risks during the construction stage. The research also confirms the benefits of

considering construction workers' OSH when making decision about the design of buildings (and other facilities).

Implications for education

The research has important implications for the education of construction industry professionals, particularly those involved in “upstream” decision-making. Design professionals' low levels of process knowledge has been cited as a barrier to the effective implementation of PtD/DfS in the construction industry. In the UK, a review of construction fatalities recommended accrediting bodies representing the construction professions establish specific requirements to include OSH in the education of all professionals engaged in the delivery of construction projects. Specific requirements to incorporate construction process knowledge into the engineering and architecture curricula could enhance the effectiveness of PtD policy initiatives. Unlike in the USA, in Australia, architects can be held accountable for injuries and fatalities in the construction process.

Report for Aim #2

Methods

Q-method is a foundation for the systematic study of an individual's beliefs, perceptions and attitudes. A Q-set is a sample of objects with ranks, different forms: statement, opinions, photos, etc. A Q-sort is the pattern that arrays objects into categories, under different conditions or requirements, no right or wrong ways or answers. The goals of Q-method are to understand human experiences and to interpret individual (or group) differences.

The methodology enables to meet the specific research aim #2 which was to investigate the extent to which different sociotechnical roles share similar perceptions of OSH risk with other members of their group and/or have different perceptions of OSH risks to members of other professional groups. The understanding generated by the analysis will identify the underlying mechanisms by which occupants of disparate professional and functional roles form judgments of OSH risk and make decisions and take actions based on these judgments.

The goal of this Q-method design was to compare construction industry stakeholders' OSH risk perceptions. In particular, whether:

- (i) different stakeholder groups (e.g. architects, engineers, constructors and OSH professionals) share similar (within-group) understandings of OSH risks in construction work, and
- (ii) there are between-group differences among these stakeholder groups.

The methodology for the Aim #2 followed six steps:

Step 1: Identification of a range of commonly used different systems or methodologies for four building elements (i.e. façade, roof, building structure and building services)

Step 2: Development of a photographic tool to be applied in the Q-sort exercise

Step 3: Development of the condition of the Q sort instruction and open ended questions

Step 4: Undertaking a Pilot test of the photographic tool and instruction with industry participants
Step 5: The collection of both quantitative and qualitative data using the photographic tool
Step 6: Analysis and reporting Q-sort data.

Specifically, this research design includes these Q-methods features as follows:

- Q-set: photos
 - representing construction processes implicit in different building systems
 - richness and accuracy of information can be conveyed in describing a scenario
- Q-sort: to subjectively judge the level of OSH risk by identifying hazards

The purpose of such settings allow us to obtain Aim #2 which was to examine whether different stakeholder groups (e.g. architects, engineers, constructors and OSH professionals) share similar (within-group) understanding of OSH risks in construction work, and whether there are between-group differences among these stakeholder groups. Four specific building systems were utilized to reflect particular OSH risk attributes, and each of which was determined by decision making in a construction project. These finalized four building systems were façade, roof, structure, and MEP services (see Figure 4). Q-sort data were collected through two approaches: one was from online Q-sort experiment and the other was from face-face interview. Results from a pilot study shown that there was not significant differences between the data from these two approaches, and therefore, both could be used reliably.

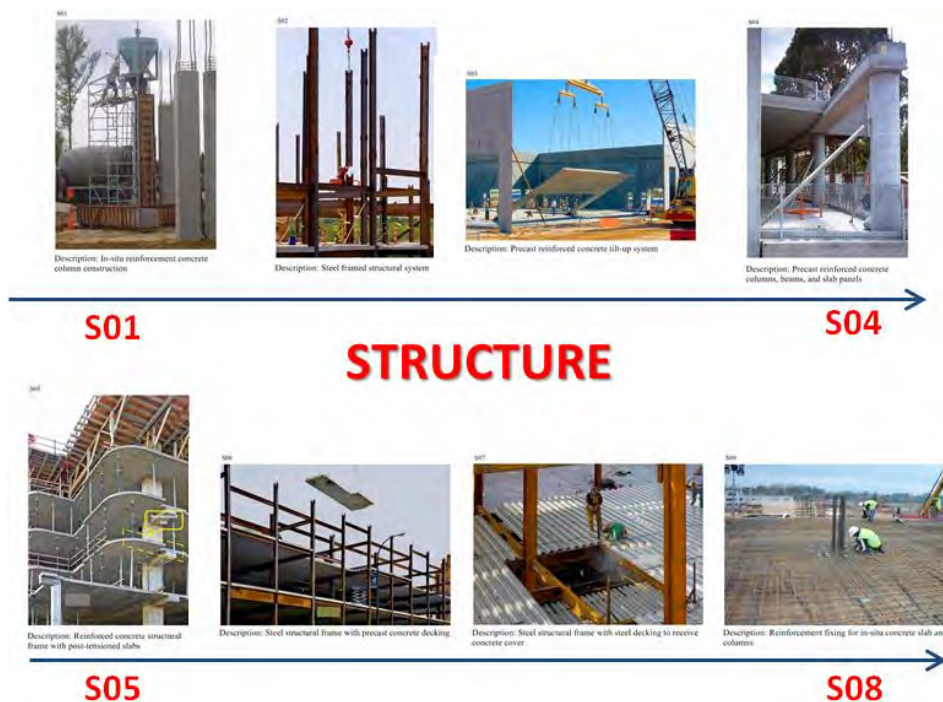






Figure 4. Q-sets photos for façade, roof, structure, and MEP services.

Participants were invited to sort the photographs individually by their likelihood of an accidental injury occurring during the course of the construction process in the photo, and severity of the consequences if an accidental injury occurs in the construction process. The five categories for assessing likelihood of accident were “Rare”, “Unlikely”, “Moderate”, “Likely”, and “Almost certain”. The five categories for assessing severity of accident were “Insignificant”, “Minor”, “Moderate”, “Major”, and “Catastrophic”. The participants were expected to concentrate on the SAFETY of the building systems shown in the photos, and evaluate safety risks associated with the construction processes in a series of open questions.

Results

The results for AIM #2 revealed that there is no absolute within-group homogeneity among professional groups nor are between-group differences always evident with respect to participants’ OSH risk perceptions associated with the selected building systems/technologies.

Findings from the Q factor analysis indicated general results that identified participant clusters produced by the Q factor analysis cut across occupational and professional groups. Although each cluster included a mix of professional groups, the results indicated that a specific professional group dominated each cluster.

The qualitative, explanatory data indicated that participants in these clusters used different frames of reference or attributes to understand OSH issues. These attributes (including technical, psychological and wider social and industrial factors) can explain differences in participants’ judgments of the likelihood and consequence of accidental injury associated with constructing different building systems. The research indicated that OSH risk is subjective in nature and individual risk perception is the result of the interplay between these attributes.

Discussion

The understanding that risk judgments are shaped by psychological and social factors suggests a multidisciplinary approach to OSH risk management in the construction project environment. Only adopting a technological approach to OSH risk analysis is inadequate to reflect the complexity of perceptions and judgments made by project participants. One reason is that technical estimates usually do not represent the 'objective' probability or magnitude of harm because technical professionals (e.g. OSH professionals) are also members of a social group, and their risk judgments are also subject to various explicit or implicit assumptions associated with membership of that group. A purely technical approach to risk analysis assumes that all causal pathways to events can be identified, which is unlikely to eventuate due to the complexity inherent in the interplay of human and technological systems. Risk should therefore be understood as being the manifestation of a combination of perceptions, social construction and objective outcomes. In the construction project environment, risk management strategies need to consider the OSH risk perceptions of all the stakeholders, who have an impact or who could be impacted by OSH risk assessment and control-related decisions.

The research results also have implications for the practical application of Construction Hazard Prevention through Design (CHPtD) or PtD or DfS in construction projects. Construction project participants perceive OSH risks in different ways. It is possible that a design solution perceived to be safe by one participant group may be perceived to be associated with a high likelihood of injury by another participant group. It is therefore recommended that all relevant project participants' risk concerns be communicated and considered in the design stage, in integrated fashion, to achieve equitable and satisfactory OSH risk control outcomes. Participants perceive risks by referring to relevant attributes. These attributions can be subject to certain biases and distortions that shape the way that people respond to OSH. The research highlights the usefulness of a photographic Q-sort process in bringing to light differences in ways of thinking about OSH within and between stakeholders groups. These differences are useful in helping to identify biases, misperceptions and differences of experience or opinion in relation to OSH risks. It is suggested that all stakeholder groups who could impact OSH, or whose OSH could be impacted by project decision-making, are engaged in a consultative processes to explore their OSH risk judgments and evaluation criteria early in the construction project life cycle. Through communication and rational discourse about the magnitude of and best ways to control OSH risks, it is anticipated the OSH experiences and perceptions of all project stakeholders can be considered in decision-making. This is likely to lead to more comprehensive and accurate assessments of OSH risk, as well as more equitable and effective OSH risk control measures.

Conclusion

The AIM #2 attempted to understand the similarities and differences in professional groups' OSH risk perceptions in the construction industry. It utilized an innovative photographic data collection method based on Q-methodology to collect data from four construction stakeholder groups. Participants were requested to make judgments about the likelihood of an accidental injury associated with the construction of a range of selected building systems, as well as the severity of consequence should any accident happen. The quantitative data analysis indicated the co-existence of within-group similarity and difference, and between-group similarity and difference in OSH risk perceptions. The Q factor analysis indicated a number of participant

clusters cutting across professional groups and interpretation of the factors revealed substantial differences between the OSH judgments made by participants in the clusters. Qualitative explanatory information revealed participants in the clusters used different attributes when considering the likelihood and severity of accidental injury. These attributes (including technical, psychological and wider social and industrial factors) shaped their sorting patterns. The results suggest shared mental models (SMMs) are unlikely to exist in construction project teams (without intervention and training), as each individual uses their own frame of reference to understand OSH.

There are opportunities to understand these different frames of reference and create more consistent team mental models of OSH. Therefore, incorporating a diversity of viewpoints into project decision-making is recommended in order to produce effective decision-making in the choice or specification of building systems.

Report for Aim #3

To evaluate the impact of collaborative project delivery methods and procurement strategies on OSH performance through the development of shared mental models of OSH and the creation of a unity of purpose with regard to project/industry OSH outcomes.

Methods

There is considerable anecdotal evidence to suggest that collaboration within the construction supply chain yields improved OSH performance. However, much of the research 'evaluating' the benefits of collaborative arrangements in the construction industry has utilized surveys and case studies, exploring industry participants' subjective views about collaboration. Researchers failed to use a robust evaluation strategy from which firm conclusions as to the benefits of collaboration could be drawn. Consequently, the true OSH benefits of collaboration within the construction supply chain are not well understood. This research proposed the use of a novel quasi-experimental design to assess the impact of collaborative procurement mechanisms on the development of shared mental models and OSH outcomes in the construction industry. The experiment sought to ascertain the effects of collaboration (in the form of project alliancing, single project partnering, and strategic partnering) on the development of a unity of purpose with regard to OSH and project OSH performance. The subsequent analysis was to contribute to the development of 'best practice' in the procurement of safe and healthy construction work.

Results

The research adopted a comparative case study approach. Data were collected from a total of 23 construction projects, 10 in Australia/New Zealand and 13 in the United States of America. For each project, features of work were purposefully identified by project participants in consultation with the research team. Features of work were selected as the unit of analysis because they presented a particular health and safety problem or challenge. What follows in the appendix, are the completed case studies, which above and beyond the scope of work. These can and have been used for training the results of this study. Additional r2p deliverables will be supplied before the end of the NCE period.



Figure 5. Cover page of a case study example.

For each feature of work, comprehensive data was collected to capture decisions that were made in relation to the design of the feature of work, the process by which it was to be constructed and the way that health and safety hazards were to be addressed. Data were collected by conducting in-depth interviews with stakeholders involved in the planning, design and construction of the selected features of work. These interviews explored the timing and sequence of key decisions about each feature of work, and the influences that were at play as these decisions ‘unfolded’ in

the project context. During the course of the research 288 interviews were conducted (185 in Australia and 103 in the USA). The average number of interviews per feature of work was 6.7.

Projects chosen for data collection represent four different construction sectors (residential, commercial, industrial, and heavy) as well as four different delivery methods (Design-Bid-Build, Design-Build, accelerated, and collaborative). This was done to help determine the role OSH plays in each type of construction project. The projects were then placed on a matrix. Table 8 represents the 14 projects studied within the United States. Table 9 shows where American and Australian projects overlap on the matrix.

Table 8. Matrix of American projects

	Residential	Commercial	Industrial	Heavy
Design-Bid-Build	Roanoke House	Dining Hall	Wastewater Tank	Highway Expansion
Design-Build	Blacksburg House	Psychiatric Hospital	Server Farm	New Highway
Accelerated	Blitz Build	Football Stadium	Chemical Plant	Bridge Project
Collaborative	Mountain House	New Hospital	Coal Plant*	Coal Plant*

**Note: The coal plant project is considered to be both an industrial and a heavy construction project.*

Table 9. Overlap of American and Australian Projects

	Residential	Commercial	Industrial	Heavy
Design-Bid-Build	US	AUS+US	US	US
Design-Build	AUS+US	US	AUS+US	AUS+US
Accelerated	US	AUS+US	AUS+US	AUS+US
Collaborative	US	US	US	AUS+US

List of publications

PhD dissertation

1. Saunders, LW: [2013] Measuring Safety Attitude Differences in the Construction Supply Chain, Ph.D. Thesis, Virginia Tech.

Journal papers

2. McCoy AP, Saunders L, Kleiner B, Blismas N: [2012] Application of Safety Project Interview Data to a Cyclical Research Model of Translation. *ASC International Journal of Construction Research and Education*, 8(4):260 - 280.
3. Saunders LW, McCoy AP, Kleiner BM, Mills T, Cooke T, Lingard H, Blismas N, Wakefield R: [2016] International Benchmarking for Performance Improvement in Construction Safety and Health. *Benchmarking: An International Journal*, 23(2) in press.
4. Saunders LW, Kleiner BM, McCoy AP, Lingard H, Mills T, Blismas N, Wakefield R: [2015] The Effect of Early Supplier Engagement on Social Sustainability Outcomes. *Journal of Purchasing and Supply Management*, in review, 2nd review.
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7. Lingard H, Pirzadeh P, Blismas N, Saunders L, Kleiner B, Wakefield R: [2015] The relationship between pre-construction decision-making and the effectiveness of risk control: Testing the time-safety influence curve. *Engineering, Construction and Architectural Management* 22(1):108-124.
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15. Zhang P, Lingard H, Blismas N, Wakefield R, Kleiner B: [2013] Application of Q-methodology in studying construction stakeholder's perceptions of OSH risks – An introduction to the preliminary stage. Proceedings of the CIB World Building Congress Construction and Society, Brisbane, Australia, May 5 – 9.
16. Zhang P, Lingard H, Blismas N, Wakefield R, Kleiner B: [2014] Analysis of difference/similarity between construction project participants' work health and safety (WHS) risk perceptions. Proceedings of the CIB W099 Achieving Sustainable Construction Health and Safety, Lund, Sweden, June 2-3.

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Research to Practice (R2P) Deliverables

RMIT University is developing an R2P document that provides a practical guide to the outputs of the research. The R2P document is due for completion in the first half of 2015. The table of contents of the document includes:

Introduction

- Background to the Guide
- Purpose of the Guide
- Research objectives and summary
- How to use this guide

Principle One: Engage in a collective effort to ensure that the best possible OSH outcome is realized

- The hierarchy of control
- Case study One: *case study where changes made achieved a high level tech. control measure*
- HOC process flowchart
- Evaluating OSH outcomes using the HOC
- Understanding the HOC measurement method.

Principle Two: Cultivate a prominent and shared view of OSH

- Principle 2 explained
- Perceptions of OSH hazards and risks
- Case study 1 - *example demonstrating significant difference of opinions with reasons*
- Analysing OSH risk perceptions in project teams

Principle Three: Identify and consult all relevant stakeholders

- Principle 3 explained
- Case study 1 - *example of external stakeholders engaged such that a potentially negative OSH outcome was avoided*
- Case study 2 – *example of a case in which internal stakeholders were consulted early to produce a good OSH outcome*
- Understanding stakeholders' interests
- Stakeholder management process
- Stakeholder analysis and engagement tools
- Case study 3 – *example of a case in which external stakeholders had a negative impact on OSH that could have been avoided*

Principle Four: Ensure construction process knowledge is available to decision-makers

- Principle 4 explained

- Case study 1 – *example of a case in which construction process knowledge was accessed resulting in a significant design change that produced better OSH outcomes*
- Early involvement of construction process experts
- Structural and organisational challenges
- Construction process knowledge mapping tool
- Case study 2 – *example of a case in which construction process knowledge was not available or not utilised in which the OSH outcomes could have been improved*

Principle Five: Continuously improve performance

- Principle 5 explained
- How effectively are we dealing with OSH?
- Benchmarking OSH performance
- Guide to benchmarking OSH outcomes
- Worked example: *comparison between two cases representing the same building element but with different HOC scores. Explain how lessons could be transferred between these two if they were benchmarked against one another.*

The Case Studies developed by Virginia Tech to be used for training and other purposes. Contact Brian Kleiner at bkleiner@vt.edu to obtain these materials.

Study Title: From Finger-Pointing to Lifesaving: A Supply Chain Approach to Construction OSH

Total Enrollment: 4 **Protocol Number:** _____

Grant Number: 5U60 OH009761 – Project ID: 648

PART A. TOTAL ENROLLMENT REPORT: Number of Subjects Enrolled to Date (Cumulative) by Ethnicity and Race				
Ethnic Category	Females	Males	Sex/Gender Unknown or Not Reported	Total
Hispanic or Latino	0	0	0	0
Not Hispanic or Latino	3	3		6
Unknown (individuals not reporting ethnicity)				
Ethnic Category: Total of All Subjects*	3	3		6*
Racial Categories				
American Indian/Alaska Native				
Asian	1			1
Native Hawaiian or Other Pacific Islander				
Black or African American				
White	2	2		4
More Than One Race				
Unknown or Not Reported		1		1
Racial Categories: Total of All Subjects*	3	3		6*
PART B. HISPANIC ENROLLMENT REPORT: Number of Hispanics or Latinos Enrolled to Date (Cumulative)				
Racial Categories	Females	Males	Sex/Gender Unknown or Not Reported	Total
American Indian or Alaska Native				
Asian	1			1
Native Hawaiian or Other Pacific Islander				
Black or African American				
White	2	2		4
More Than One Race				
Unknown or Not Reported		1		1
Racial Categories: Total of Hispanics or Latinos**				6**

* These totals must agree.

** These totals must agree.

Project ID 652 – A Decision Support System (DSS) for Ergonomic Construction Design

Sponsor

National Institute for Occupational Safety and Health (NIOSH)

Grant #

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Final Progress Report

by

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ABBREVIATIONS

CCW	counter clockwise
CHPtD	Construction hazard prevention through design
CONN	connectivity
CW	clockwise
DfCS	Designing for Construction Safety
DDS	Decision Support System
EF, k1	EMG-to-force relationship
EMG	electromyography
EO	external oblique
FIT	Fittability
FL	force-length relationship
FP, k2 muscle	passive components
FV	force-velocity relationship
GTD, k3	global time delay
ILL	iliocostalis lumborum pars lumborum
ILT	iliocostalis lumborum pars thoracis
IO	internal oblique
LI	Lifting index
Li	length of ith muscle
LBP	low back pain
LTL	longissimus thoracis pars lumborum
LTT	longissimus thoracis pars thoracis
MF	multifidus
MVC	maximum voluntary contraction
nEMG	normalized EMG
PCSA	physiological cross-sectional area
PtD	Prevention through Design
RA	rectus abdominis
REBA	Rapid Entire Body Assessment
RPE	ratings of perceived exertion
sEMG	surface EMG
SF&SE	muscle stress for flexor and extensor
WMSD	Work-related musculoskeletal disorders

ABSTRACT

Our Decision Support System (DSS) is intended to provide designers with an evaluative tool for mitigating ergonomic hazards at the design stage (i.e., “Prevention through Design” or PtD). Specific application is to residential construction using panelized (prefabricated) walls, to take advantage of the centralized (panel) design involved. Work-related musculoskeletal disorders (WMSDs) are prevalent among residential construction workers; our long-term goal is to reduce these disorders, particularly those related to the handling of panelized walls. Our work addresses the need for improved PtD, specifically by providing a software system that can be used by panel designer and other related parties. As such, changes at the design stage in the construction life cycle can positively impact a large number of construction sites and workers. Our multidisciplinary approach included both ergonomics and production issues as fundamental components, and both are improved through use of the system. It thereby addresses the need to support the economic/business case for PtD and increases the likelihood that the system will be used.

We conducted several phases of work involving a combination of field measures and surveys, task analyses, algorithm and software development, computer-based simulations, and lab- and field-based assessments. We interacted with a large residential builder and two panel manufacturer/installers, regarding their practices and potential barriers to incorporating our DSS in their processes and to determine effective strategies to implement the DSS in practice. We also interviewed several panel assembly crews to identify their existing construction rules and strategies. Three additional “developmental” activities were completed. First, we substantially improved our decision-making algorithms for and simulation of the processes involved in panelized residential construction. Second, we completed additional lab-based studies to aid in ergonomic assessments of simulated panel construction tasks. Third, we developed and completed a preliminary evaluation of methods to facilitate ergonomics assessments for a broad range of tasks. In the final stage, we conducted computer-based and field evaluations of the DSS efficacy and effectiveness. Respectively, these indicated areas for future emphasis (e.g., panel stacking appears to be a major “driver” of worker demands) and suggested that substantial improvements in productivity and physical demands are jointly achievable.

Our software considers complex, multi-worker physical processing scenarios, for which new simulation methods had to be developed. We also needed to develop new methods for ergonomic assessment in such scenarios, which are characterized by a very wide range of activities, and used a novel application of classical lean manufacturing concepts. These contributions are generalizable to other workplace problems. Our software tool is still the first to consider ergonomic and production aspects in an integrative manner for such complex systems. Subsequent work is planned to: 1) complete analysis of simulated-based assessments of DSS efficacy, 2) conduct additional field testing of DSS effectiveness, 3) conduct longer-term, longitudinal evaluations of the DSS in a field setting; 4) work with software and/or panel manufacturing companies to facilitate continued and expanded use of the DSS; 5) apply the “lessons” learned from developing and applying the DSS to additional work domains within and outside of the construction sector.

SIGNIFICANT (KEY) FINDINGS

This project involved three separate components, with an overall objective of finalizing and applying a Decision Support System (DSS) to enhance both ergonomics and productivity in panelized residential construction. The first component addressed the assessment of ergonomics in panelized construction, especially musculoskeletal aspects. A new biomechanical model was developed to assess low-back loading, and assessments of this model indicated that satisfactory performance was possible for a wide range of manual handling tasks relevant to panelized construction. In addition, extensive lab-based task recreations were completed (some aspects of which were conducted in an earlier funded project), and used to assess important influences of task-related factors on low back injury risks. Injury risks were found to be high overall, quite high in some cases, and with important main and interactive influences of task factors including panel weight, origin height, and the number of available workers. Only a subset of the vast number of possible combinations of task factors could be tested in the lab, yet there is a need in the DSS to generate ergonomic assessment. To address this, preliminary work was completed on methods to make more generalized task-based predictions, via interpolation/extrapolation, from compiled experimental data. The success of such predictions appeared to be substantially task dependent, as well as depending on the specific assessment measure/metric employed. This latter work is ongoing.

The second component involved substantial refinements to an earlier prototype DSS. Fundamental lean concepts and principles were applied through new algorithms to address the first two of these problems. Results from computational experiments indicated that this approach results in improved performance, has general applicability, and outperforms several existing methods. The discrete-event panelized residential construction simulator, an integral component of the noted prototype and current DSS, was substantially refined and expanded. For this, existing approaches were not appropriate, and thus a new approach was developed based upon elements of earlier methods. This new approach was needed for system-level simulation of panelized residential construction, as this is a complex, multi-worker physical process. Subsequently, algorithms were developed and incorporated into the DSS based again on lean concepts and principles. Preliminary results from a field study are presented (additional work is ongoing), involving a pair of houses (one constructed the “traditional” way and one guided by the DSS). These results show that the approach can simultaneously improve productivity, construction workload, and worker injury risks.

In the third component, methods for file-based ergonomic exposure and risk assessment were developed and assessed. A wearable system for tracking worker postures and motions during manual handling tasks was assessed in a lab setting, with results indicating the conditions under which such systems can perform favorably or otherwise. A second study developed methods to integrate this wearable system with another system that tracks in-shoe pressure; results indicated favorable performance of some methods, and which can facilitate more comprehensive ergonomic assessments in future field research. Two additional studies assessed methods for analyzing the extensive data obtained from such wearable systems, and indicated which approaches are more effective. Several novel algorithms have been developed to address these three problems; our approach stems from several fundamental principles, many of which are based on concepts derived from lean manufacturing.

A variety of algorithmic and heuristic software applications were developed and implemented, as were fundamental and applied contributions regarding the application of lean methods in construction, modeling of complex physical processing systems involving humans, the task-dependency of ergonomics risks, ergonomics assessments, and field data

collection/processing. Preliminary results indicate the broad and substantial potential benefits possible using the DSS.

TRANSLATION OF FINDINGS

Our results support several specific recommendations and general guidance to prevent workplace injury in panelized residential construction (and beyond).

- There are inherent barriers to the use of prevention-through-design (PtD) to reduce ergonomic exposure in residential construction. PtD tools (software) must accommodate or address current design, manufacturing, and construction practices, limitations, and constraints.
- There are complex effects of major panel design parameters and worksite aspects on physical exposures and injury risks, often with potentially opposing influences on ergonomic and productivity aspects. This emphasizes the need, in such complex work situations, for a system that can collectively consider physical demands and productivity and that allows users to assess the tradeoffs involved.
- Addressing production and ergonomics jointly in panelized residential construction via optimization methods is computationally infeasible. Instead, heuristic methods coupled with discrete-event simulation provides a suitable approach for this problem. However, new simulation methods are needed for this complex system.
- Integration of traditional lean engineering concepts and principles can feasibly and effectively be implemented in jointly enhancing production and ergonomics.
- Methods developed in this work indicate such joint consideration is feasible and practical through the use of simulation and lean methods, and that substantial improvements are possible.
- Both predicting ergonomic risks and processing of extensive field ergonomic measures are challenging problems, for which new methods and approaches are still required; preliminary results, however, has provided some guidance on potentially useful methods.

OUTCOMES / IMPACT

Findings from the present work offer several areas of guidance for future investigations and research, both to continue a process to improve panelized wall construction and more generally to achieve PtD in this sector and others.

- The core of our approach –system-level simulation of complex tasks comprising a job together with task-based ergonomics assessments and heuristics to facilitate decision making – should be considered a viable approach for other jobs and/or sectors. Such an approach should be applicable wherever there is (or could be) a central design effort, and has the potential for substantial “downstream” positive effects.
- Our work has identified several gaps in the area of ergonomic risk assessment. Specifically, future work is needed to improve the ability to predict ergonomic risks, to support predictions over a wider range of tasks (i.e., to minimize the need for extensive data collection). Future work is also needed to provide both conceptual and practical approaches to: 1) compiling ergonomic assessments either across different types of exposures and body regions, or across multiple workers; 2) including time-dependent effects of exposures (e.g., related to task sequencing or fatigue); and 3) processing extensive ergonomic data obtained from wearable systems.
- Subsequent investigations should assess the use of such decision support tools: 1) for training and education; 2) to identify safety (in addition to ergonomic) concerns; 3) as a method to specify worker accommodations.
- Use of new discrete-event simulation methods, as well as lean concepts and principles, may provide powerful new PtD tools and approaches.

SCIENTIFIC REPORT

1. Background and Significance

1.1 Epidemiological Evidence in Residential Construction

Our primary motivation is to reduce the prevalence of occupational injuries among residential construction workers. Residential building construction in the U.S. is the seventh largest industry, involving about 4% of annual national economic activity (NAHB Research Center, 2002) and 7% of the workforce (NIOSH, 2004). There were over 1 million residential construction workers in 2006 (Mullins, 2006); this sector is projected to grow by ~17% in the coming decade (BLS, 2007), and roughly one third of all carpenters are involved in the construction of buildings (BLS, 2009). Despite recent downturns, new privately owned housing units authorized through permits continue at roughly 1 million per year (U.S. Census Bureau, 2009). Of particular relevance here, WMSDs are prevalent in residential construction. Compared to the general workforce, occupational injury rates are high in construction, with over 150,000 nonfatal workplace injuries and illnesses reported in the U.S. in 2005 (BLS, 2005). Roughly 20% of these were attributed to overexertion and repeated motion, and WMSDs are more common in the construction industry than in any other sector except for transportation in the U.S. (Weinstein et al., 2007). Occupational injury costs in construction are particularly high in residential construction (Lipscomb et al., 2008a; Waehrer et al., 2007a) and among laborers and carpenters (LeMasters et al., 1998; Waehrer et al., 2007b). In Washington State, residential building construction was among the three highest industry groups for the most common and costly occupational injury types (Bonauto et al., 2006).

Although BLS data are the most common source of construction-related injury statistics, these do not fully capture differences between residential construction (the focus of our work) and other construction sectors. Dement and Lipscomb (1999) found an overall and relatively high rate of cases (16.4 per 200,000 hours) for a 7-year period ending in 1994, with no obvious increasing or decreasing trend. When examined by the nature of injury, muscle strain was identified most frequently among all other mechanisms, and except for minor injuries, the back and shoulders were by far the most frequent sites of injury. Hence, *ergonomics issues are particularly relevant in residential construction*. When examined by construction trade or skill, carpenters had the highest number of cases and were among groups with the highest rates. Similar results have been recently reported (Waehrer et al., 2007b; Lipscomb et al., 2008a,b).

Actual rates and severity of morbidity in residential construction may be even higher than such evidence indicates. National surveillance systems have been suggested to underestimate actual values (Lipscomb et al., 2008a) by as much as 60% (Rosenman et al., 2006), and less than 10% of construction WMSDs appear annually in the worker compensation system (Morse et al., 2005). Further, WMSDs limit the capability of construction workers and lead to an increase in occupational disability (Arndt et al., 2005). There are also long-term physical consequences of construction work, in that retirees from construction work have poorer health, less time to spend on daily activities, and higher levels of pain compared to nonconstruction retirees (LeMasters et al., 2006).

1.2 Current Approaches to Safety in Construction

Extensive literature has addressed safety planning and provided practical strategies for preventing accidents and injuries (e.g., MacCollum, 1995; Levitt and Samuelson, 1993; Hinze, 1997; and Goetsch, 2003). Traditional approaches involve introducing a safety program in a construction company. These programs involve such activities as establishing responsibility in the construction organization, developing a project safety program, observing OSHA regulations, analyzing hazards, and having safety meetings (e.g., Hinze, 1997). Such traditional programs generally consider construction safety as a site-based problem and give little consideration to changing the design of the constructed facility or limiting hazards by changing the construction process. The problems faced become more substantial as the size of the construction organization diminishes. At present, residential construction is a craft-based enterprise driven by a design but disconnected from the actual method of assembly and its impact on the human worker. Whether the design is a customized or spec structure, modern designers are typically removed from most on-site production activity and rely heavily on a distribution of subcontractor construction and installation knowledge associated with the various systems that comprise a house. These subcontractors are provided with little or no guidance on acceptable construction methods, other than material specifications and schedule expectations (e.g., O'Brien et al., 2000; Wakefield et al., 2001; O'Brien et al., 2002).

Controlling WMSDs in construction can be more difficult than in many other industries (e.g., Vedder and Carey, 2005). Field studies are hampered by noncontinuous employment and a changing and unpredictable workplace (Ringen and Stafford, 1996), as well as by substantial task variability and irregular work periods (Forde and Buchholz, 2004). These, and an often complex project and organizational configuration, make construction a “demanding sector in which to conduct research” (van der Molen et al., 2005). As a whole, the construction industry has been slow to address construction safety and even slower to address ergonomics issues. While the industry is complex, it is not unique either in terms of the potential benefits from incorporating industrialization and reducing ergonomic exposures, both of which can be obtained through improved design.

1.3 Role of Construction Design in Safety

Prevention through Design (PtD) – also Construction Hazards Prevention through Design (CHPtD) and Designing for Construction Safety (DfCS) – has received increasing attention as a means to reduce safety hazards. The goal is to encourage designers and architects to consider safety early in the project life cycle (e.g., Behm, 2008; NORA, 2008; Schulte et al., 2008; Toole and Gambatese, 2008). While roles for contractors and employees later in the life cycle are still acknowledged, CHPtD is justified by the lost opportunities when interventions are considered only later in the life cycle (e.g., Fadier and de la Garza, 2006). Safety in (construction) design has been promoted and studied in the construction industry by several groups (e.g., Gambatese et al., 1997; Gambatese and Hinze, 1999; Hecker and Gambatese, 2003; Weinstein et al., 2005; Behm, 2008; Toole and Gambatese, 2008). In this approach, primary attention is given to eliminating hazards through changes in work practices, substitution, or redesign, with an expectation of improved outcomes relative to other approaches in the hierarchy of control strategies (Roland and Moriarty, 1990; Sweeney et al., 2000). More specifically, it is argued

that construction designers can substantially influence construction site safety by integrating safety considerations during the design process (Gambatese and Hinze, 1999). A substantial fraction of injury-causing accidents stem from conditions “upstream” in the supply chain of the actual construction process, at the stages of planning, scheduling, and design (Gambatese et al., 2005; Weinstein et al., 2005). Analysis by Hecker and Gambatese (2003) suggests that more than half of construction accidents can be eliminated, reduced, or avoided with more attention during design. Our approach (described below) is consistent with this safety in design concept, though modified to address *ergonomic concerns* (i.e., exposures and risks).

1.4 Need for Tools to Facilitate PtD

Given the potential for design impact in safety (and arguably ergonomics), what accounts for the lack of more substantial designer involvement (Hinze and Wiegand, 1992)? Several explanations emerge from the work of Gambatese and colleagues (Gambatese et al., 1997; Gambatese and Hinze, 1999; Hecker and Gambatese, 2003). Construction designers have limited education and experience related to construction processes and safety, and we have found comparable results with respect to ergonomics (Kim et al., 2008). A pervasive attitude maintains that construction work is inherently unsafe and that design has a minimal impact on safety, again reinforcing the perception that the industry is unique. Compounding this attitude is the traditional construction model, in which there is a strict financial and legal separation between the design professionals and process and the contractors/constructors. Additional barriers include the range of stakeholders involved, large numbers of small companies (subcontractors), limited resources, and limited control of workplace conditions by subcontractors (van der Molen et al., 2005). More generally, the fragmentation of the homebuilding industry is a barrier to innovation (HUD, 2005). Yet, enhancing construction safety through design is becoming more common, often via legislation (Lin and Mills, 2001; Hecker and Gambatese, 2003; Gibb, 2004; Lam and Chen, 2004; HMSO, 2007). In the U.S., there appears to be at least a willingness to implement safety in construction design (Gambatese et al., 2005). To capitalize on this willingness, and to achieve the potential benefits of ergonomics in construction design, the barriers identified above must be overcome. One particular barrier impeding the implementation of safety in design is the lack of tools or guidelines (Gambatese et al., 2005).

Several such tools exist, most of which address safety hazards related to acute trauma (e.g., falls). These are primarily software tools that assist with safety analyses in construction design (e.g., Gambatese et al., 1997; WorkCover, 2001; Design for Construction Safety Toolbox, CII; Hadikusumo and Rowlinson, 2004; Wakefield and O'Brien, 2004). These tools do not address ergonomic issues, and none address aspects other than safety (e.g., issues related to production). While ergonomics is addressed in the “Decision Support System” of Womack and Armstrong (2005), it is essentially a repository of detailed job information and ratings of upper extremity physical stress. A number of commercial packages are also available, some of which incorporate ergonomic evaluations along with human simulation and animation (e.g., EDS, 2004; Human Solutions, 2004; Delmia, 2009). Lack of demonstrated empirical validity is one reason to avoid use of existing commercial packages (and published algorithms). Perhaps more importantly, commercial packages are cost-prohibitive (in the 10s of thousands of dollars)

and require extensive training. It is thus unlikely that such methods will receive widespread adoption soon, particularly for the smaller firms involved in residential work.

1.5 Panelization

Our efforts to facilitate ergonomics in residential construction design are focused on the development of a CHPtD tool and are intended to enable designers and other decision-makers to incorporate ergonomics (and production) issues into their design process for one aspect of residential construction. We have focused on construction using panelized walls because of the complexity of the construction process, increasing adoption of panelization, and existence of a central designer. Panelization (i.e., the use of panelized walls) is exemplary of the current trend in residential construction of increased use of premanufactured components. In contrast to traditional stick-built walls, which involve assembling and erecting walls from relatively raw lumber (e.g., two-by-fours plus sheathing), panels arrive at the work site more completely assembled and are typically delivered on pallets containing 15-40 panels stacked 1-3 meters high (Figure 1.1). A panel designer, working from an architect's drawing, specifies panel sizes (usually lengths) and several aspects of preassembly (i.e., from wood only to complete with sheathing, conduit, insulation, etc.). A carpentry crew then transfers and erects the panels at required locations on site.



Figure 1.1. Workers lift a sheathed panel from a stack on a pallet.

Previous work (Wakefield et al., 2001) has documented the present shift among residential U.S. production builders to panelized construction. Wakefield and O'Brien (2004) indicated that most new homes in the U.S. include some form of wall panels and that panels comprised ~5% of all walls in residential construction (or ~65,000 houses). Recent reports (Toole and Gambatese, 2008; BLS, 2009; NAHB, 2009) have emphasized the increasing use of prefabricated components in construction, including wall panels. Panel use appears to be more prevalent for multifamily homes and in certain regions of the country (U.S. Census Bureau, 2007). In one case study (NAHB, 2009; SBCA, 2009), construction of a 2,600-sq.-ft. home with trusses and panels took just 37% of the time required to construct a traditional stick-built home, used 26%

less lumber, generated 76% less waste, and reduced total labor and material costs by 16%. Panelized construction also reduces the need for skilled labor and the risk of theft on site (Shepard, 2000). While the panelized approach provides unmistakable savings in many areas, present construction methods may also result in *greatly increased risk of worker overload and injury*. As panels are produced in a factory, production- and transportation-related objectives are typically employed. As a result, panels can be either too large for workers to handle or too small, resulting in increased material handling.

Panelization is also representative of other premanufactured construction activities in the separation between the design activity and the post-design activity undertaken by a subcontractor (i.e., builder). Panelization within the building industry, however, provides an opportunity to develop an ergonomic analysis tool, since the centralized panel designer can impact a large number of construction sites and workers. Further, decisions made by such intermediate decision-makers can substantially reduce the downstream decision variability that leads to risk. In the design stage, however, little consideration is given to the effects of panel design on the construction process or worker (O'Brien et al., 2002; Kim et al., 2008). This example is representative of the residential construction process in general, in which there is extensive fragmentation and process design and integration are rarely considered. Work crews are left to their own devices to design a construction process for panel erection and ultimately have an increased exposure to hazards and injury risks. As an example of the physical demands involved, we used the NIOSH Equation for manual lifting (Waters et al., 1993, 1994) to assess 174 panel lifts observed at construction sites (Nussbaum et al., 2009). Both one- and two-person lifts were analyzed for two types of lifts. Lifting Indexes were typically high (Figure 1.2), and <1 (i.e., relatively safe) *only for a small proportion of small panels*. A given panel mass also resulted in a significantly higher lifting index when a vertical lift was performed, suggesting the importance of work practices (or construction rules).

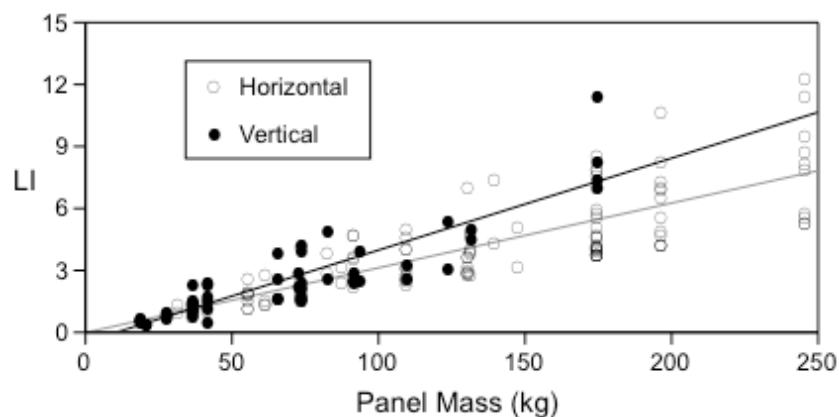


Figure 1.2. Lifting index (LI) as a function of panel mass. Linear trends are illustrated for the two lifting methods (panel held in a horizontal or vertical orientation).

1.6 Approach to Implementing PtD in Panelized Residential Construction

As discussed above, the panel designer can impact a large number of construction sites and workers. Our PtD approach encompasses not only panel design, however, but also all downstream activities up to and including on-site construction. These activities include determining how panels will be arranged into stacks for delivery to the job site, when stacks are to be shipped, where they are to be placed on arrival, what tasks should be used for each panel, which workers should work on each panel and when.

Thus, we have a sequence of related design and planning problems to solve, and implement PtD at each step of the process. Broadly speaking, two approaches are possible: (i) model mathematically and attempt to solve optimally, or (ii) develop approximate solution methods (*heuristics*) and use computer simulation to generate alternative, feasible solutions. Mathematical models explicitly considering the human worker are almost nonexistent, due to the inherent difficulty in predicting human motion and behavior (e.g., Chryssolouris et al., 2003; Park et al., 2005; Lodree et al., 2009). Additionally, our mathematical modeling efforts have shown that the problems are both too complex for accurate solution and too large for optimal solution in reasonable amounts of time. Thus, we take the second approach involving heuristics and computer simulation.

The problems of designing panels, determining how they are to be erected, and controlling the construction processes are very similar to product design, process planning, and operations planning in the manufacturing industry. The latter have been widely studied, and heuristic solution methods (many incorporating computer simulation) are well established. In product design, for example, design-for-manufacture/assembly (DFM/A, e.g., Boothroyd et al., 2001) has been used for many years to design products that are easy for workers to fabricate and/or assemble. Typically, a set of DFM/A “rules” (heuristics) are invoked during product design and used to guide the design process. Computer-automated process planning (CAPP, e.g., Chang, Wysk and Wang, 1991) has been available since the mid-1980s to automatically generate process plans in specific manufacturing applications. One method, generative process planning (GPP), utilizes a set of sequential decision rules for generating process plans automatically, based upon the product drawing (e.g., Pande and Kumar, 2008). In many manufacturing facilities, production is controlled by local decisions based upon rules that have been shown to perform well. One excellent example is the use of *dispatching rules*, whereby workers select the next job to run at their machine in real-time, based upon prespecified criteria (e.g., Mizrak and Bayhan 2006; Jungwattanakit et al., 2009). Each of the noted manufacturing problems has been successfully addressed using heuristics. In a similar manner, we envision developing a set of “design-for-construction” rules (heuristics) for panelized residential construction.

A decision-support system (DSS) is the best choice for the above approach since multiple users will be involved during different PtD activities and users will require the ability to test various alternatives and adjust final solutions. To evaluate a given set of rules for a particular building, the resulting construction process is simulated on a computer. Data obtained from laboratory-based experiments are used to generate predictions of ergonomic risk (e.g., of a low-back disorder) when that construction process is employed. While it is possible to generate such predictions directly via computer simulation (or other methods such as control theory,

optimization, neural networks, etc.), few of these methods have been quantitatively evaluated. Those that have been investigated have failed to generate reasonable levels of accuracy, except under limited circumstances. As posture and motions have a major influence on both physical demands and worker capacity, accurate estimation is essential for ergonomic exposure assessment. Thus, laboratory-based data is believed to be the best choice for generating estimates of ergonomic risk associated with a given construction process.

In addition to using computer-based simulation to evaluate the construction process, we also use it to generate a three-dimensional *simulation animation* of the process. This animation will aid construction designers, managers, and others in visualizing how a given structure is to be erected in the field. Such visualization not only improves understanding of the process, but aids in subsequent evaluation and decision-making. Use of simulation animation for this purpose is well established in manufacturing (e.g., Shewchuk et al., 2002), but has only recently been seen in the construction domain (e.g., Hadikusumo and Rowlinson, 2004). In construction planning, implementation of PtD will be greatly facilitated through the use of tools that aid the visualization of hazards (Gambatese, 2008).

1.7 Summary and Relevance

There is an increasing trend toward premanufacturing in construction, including the use of panelized walls. Current panel design approaches lead to both inefficiency and WMSD risks, negating some of the expected cost reductions intended by panel use. The centralization of panel design, however, provides an opportunity to enhance such efficiencies and reduce ergonomic exposures. We have developed a prototype DSS for panelized residential construction that facilitates a proactive approach to ergonomics and addresses the ongoing need for appropriate design tools to facilitate PtD. As it incorporates ergonomic aspects throughout the construction process, the overall impact of DSS use is expected to be more efficient and effective than reactive, site-based interventions applied only later in the product life cycle. A primary advantage in our multidisciplinary approach is the inclusion of both ergonomics and productivity as fundamental components and the joint improvement of both. As such, our approach addresses the need to support the economic/business case for PtD (e.g., Gambatese, 2008; Lin, 2008), specifically by providing information relevant to necessary financial considerations in decision-making and an understanding of the financial implications of PtD. Our system also serves as an “integrating mechanism”; from a sociotechnical systems perspective, such mechanisms help overcome the traditional challenges involved when there are multiple functional units (Hendrick and Kleiner, 2001), such as architects, engineers, and builders in construction. Finally, several authors have noted current research and practice needs related to interventions, specifically the dearth of available solutions and the lack of high-quality evaluative studies (van der Molen et al., 2007; Watterson et al., 2007; Lehtola et al., 2008; Rinder et al., 2008). Our DSS, from conception, was intended to address these needs by facilitating the development and assessment of interventions to reduce ergonomic exposures and risk.

In completing this work, we have refined, tested, and deployed the DSS; this system generates alternative panelization designs, stacking plans, and construction plans rapidly and inexpensively. In general, this system provides a framework for ensuring that construction worker health and safety is considered early, starting at the design stage of the construction life cycle, thus promoting safe field construction. Specifically, the software helps designers to quantitatively establish, evaluate, and improve the ergonomic and production consequences associated with design alternatives. This work also provide a business-case for using the DSS by demonstrating, in both simulations and field studies, its potential economic and ergonomic values. This work and the system can serve as a model for other relatively comprehensive prevention-through-design (PtD) efforts.

This project addresses two Strategic Goals within the NORA (2008) National Construction Agenda (7.0: Musculoskeletal Disorders and 13.0: Construction Hazard Prevention through Design (CHPtD)) and several of the Intermediate, Research, and Research-to-Practice Goals within these two Strategic Goals:

- Research goal 7.3.3: Develop ... exposure assessment methods(s) that can be used to evaluate exposures to WMSD risk factors....
- Research to Practice goal 7.3.4: Disseminate the exemplary exposure assessment method information to stakeholders
- Research goal 7.5.1: Evaluate interventions that are currently available to reduce or eliminate task-based exposure to physical risk factors for WMSDs
- Research goal 7.5.3: Develop and evaluate (in collaboration with industry stakeholders) interventions for high-risk tasks for which no interventions exist
- Research goal 13.1.3: Collect basic materials, case studies, and business case models needed for effective demonstrations of concepts and strategies
- Research goal 13.2.3: Characterize economic aspects associated with implementing CHPtD concepts
- Research-to-Practice goal 13.4.7: Develop tools such as educations documents, checklists, databases and interactive software to enable designers to perform CHPtD
- Research goal 13.3.3: Evaluate if CHPtD can provide secondary benefits such as ... improved work efficiency and constructability
- Research goal 13.5.1: Partner with interested and influential owners, clients, investors, professional groups, contractors, and other stakeholders to develop innovative CHPtD demonstration projects

1.8 Overview of DSS

Given the building plan (blueprint) for a home, we divide the required decision-making into three steps. The first is concerned with establishing the **panelization design**, i.e., what panels to employ (dimensions, quantity of and location of openings) for a given plan. Next, we establish the **stacking plan**, which involves how panels are to be arranged into stacks, the stack delivery locations, and the stack delivery sequence. Finally, we generate the **construction plan**: how panels are sequenced for construction followed by which construction tasks are to be used and which workers perform which tasks.

To establish how good a particular solution (panelization design, stacking plan, and construction plan) is, three measures are employed: 1) some aggregate measure of overall ergonomic risk, 2) the quantity of workers used, and 3) total construction time. The overall objective in design and planning is to minimize one of the three measures, subject to specified constraints on the other two. Thus, ergonomic aspects are considered directly in formulating the panelization design, stacking plan, and construction plan, an approach that should improve worker health, safety, and performance (van der Molen et al., 2005). Previous efforts to develop computer-aided software tools for construction planning (e.g., Chantawit et al., 2005) have separated ergonomic aspects from construction planning and scheduling. However, our goal is to *address ergonomics in both design and planning*, consistent with the PtD concept and approach discussed earlier).

We assume that a finite set of alternative materials and configurations are available for panelization and that a finite set of generic construction tasks are identified and quantified with respect to ergonomic exposures (e.g., postures, spine loads) and performance (e.g., task time). Furthermore, the generic construction tasks and exposures are used to predict ergonomic risk (e.g., of a low-back disorder) and performance for any particular construction task and panel definition. Additional assumptions are: 1) workers are identical with respect to risk and performance, 2) task time and ergonomic risk are deterministic, 3) no defective panels, 4) negligible setup time for tasks, and 5) construction tasks have 100% likelihood of being completed successfully on the first try (i.e., no rework). Each assumption can be relaxed, pending collection of appropriate data.

As noted previously, we employ heuristic (approximate) solution methods and then **simulate the entire construction process**, from panel stacks arriving at the construction site through completed construction of the panelized building. Such simulation has been shown to be an effective technique to evaluate decision-making on construction sites (Shi, 2003; Gambatese, 2008). Detailed output (ergonomic risks, worker utilization, etc.) is generated from the simulation, and a simulation animation allows the user to “see” the construction process in action and assess, for example, how the workers must work together and how the various construction tasks are performed. Of note, while the construction tasks for each panel and construction schedule are established as part of construction planning, simply providing these items to workers and expecting them to follow them is not the intent. Workers may be unable and/or unwilling to work in this manner or tasks may be short and numerous enough that time is wasted checking the schedule. Additionally, emphasizing adherence to a rigid construction schedule can result in reduced productivity and quality, such that the actual schedule benefits may be barely worth the effort (Nepal et al., 2006). Our approach is to instead provide workers with a set of construction rules; when followed, the rules result in the desired assignment of construction tasks and construction schedule. (Note that our approach, including the use of construction rules, does not rely on English fluency among workers, but does assume that an accurate translation is available and that the rules are transmitted and employed.) Our approach also has the advantage of allowing workers (and supervisors, contractors, designers,

etc.) to react to changes and unplanned contingencies that might quickly invalidate plans made in advance.

Detailed operation of the DSS is described below. In brief, each of the involved parties (panel manufacturer, transport company, contractor) uses the DSS to establish the design rules to use for their associated activity (panelization, stacking, and construction). These design rules can either be completely specified by the users or a small subset can be provided and the DSS will select the rest automatically (to minimize overall ergonomic risk, the quantity of workers needed, or the total construction time). Either way, the results are used as follows. The panelization design and stacking plan are provided to the panel manufacturer and transport company (if an external agent is used), so that panels can be manufactured and delivered accordingly. Construction rules are provided to the job site and communicated to the workers, who then perform their own decision-making during the building process. To check that construction is proceeding according to plan, the construction schedule can also be provided.

1.9 Contributions

More complete descriptions of the work completed, along with development and operation of the DSS system, are provided in subsequent sections. In the first section, results from lab-based studies are described. These addressed physical demands occurring during a range of tasks involved in the residential construction process using panelized walls. This section also includes preliminary results regarding methods developed to predict ergonomic risk for the wide range of panel-handling tasks that occur in the field (i.e., interpolating and extrapolating from the discrete testing conditions completed in the lab). Results from these experiments were incorporated in the DSS. In the second section, the development and operation of the DSS are described in three parts. First, the use of lean principles to organize and locate panel stacks is explained. Second, our development and implementation of new methods to simulate panelized construction as a complex, multi-worker physical process is presented. Third, the use of a lean approach for implementing the simulation approach is given, along with preliminary results from a field-study in which a pair of houses were completed and compared. The third section describes and evaluates new methods developed for obtaining high-precision physical exposures and for extracting useful exposure and risk measures from the high-dimensional data so obtained.

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2. Specific Aims

We proposed to continue our previous work performed as part of the Virginia Tech Center, specifically the subproject entitled “A Decision Support System (DSS) for Ergonomic Construction Design.” We have developed a prevention-through-design (PtD) approach for integrating diverse ergonomic aspects into the main activities comprising the construction life cycle and have shown how the approach can be implemented via a DSS. Our objective was to determine how each construction life cycle activity is best performed, considering the ergonomic impacts on workers in the process, and then to simulate the construction process to establish the resulting ergonomic and production implications. This approach has been implemented for a subset of construction tasks, specifically those related to construction using prefabricated walls (aka panels). Panels are being used with increasing frequency, yet contemporary design approaches lead to both inefficiency and high levels of physical demands on construction workers which are counter to the presumed cost reductions achieved from panel use. The DSS allows for rapid assessment of design alternatives and should facilitate adoption of improved designs. Our initial funding was provided to obtain relevant data and to build a prototype DSS. To refine the DSS to be both usable and used by consumers (e.g., panel designers and contractors), and to evaluate the ability of the system to improve the construction design process, we must complete several additional steps. Specifically, we planned to conduct laboratory-, computer-, and field-based studies to 1) improve and evaluate the DSS, and our ability to simulate and visualize (via computer) the tasks involved with panelized wall construction; 2) determine, by working with both designers and contractors, how best to implement the PtD approach (via the DSS) and to improve the business case for its use; and 3) conduct several case studies to demonstrate and quantify the actual and potential benefits of our system (i.e., versus contemporary approaches).

Specific Aim 1: Improve and evaluate the decision-making logic in the DSS and our ability to simulate and visualize tasks involved with panelized residential construction. Use of the DSS requires the selection of specific design rules from a set of alternatives (rule base); simulation is then used to establish how the panels are designed and shipped and how construction proceeds. In the initial project, these rules were developed empirically; further work is needed to determine the effectiveness of the rules and to refine them as necessary. To improve usability, detailed simulation input data must be obtained, the simulation model validated, and simulation capability and animation fidelity refined. We expanded our exposure database using lab-based measures and developed and evaluated methods to predict exposures and risks for a wide range of construction activities.

Specific Aim 2: Determine effective strategies for implementing the PtD approach in practice (via the DSS) and improve the business case for its actual use. A high level of interest in the DSS has been expressed by panel designers, manufacturers, and contractors who are currently using (or considering) panelized residential construction. We aimed to collect more formal and complete information from such consumers, through interviews and software use/evaluation, to determine how the DSS might be best implemented and to modify the system (as required) to ensure its utility and usability. We used the DSS (as refined in accordance with Specific Aim 1) to conduct several computer-based case studies to support this as a PtD approach. By generating panelization and stacking plans with the DSS, and by comparing them with plans developed in the “traditional” manner, we quantified these effects and thereby help convince these parties that our approach is viable and valuable. We also expanded the scope of our research to consider the “upstream” impacts of the approach, as it is clear that it will affect panel manufacturers and shippers.

Specific Aim 3: Demonstrate and quantify potential and actual benefits of using the DSS in the field. Specifically, we planned to partner with at least one panel manufacturer and several residential contractors. With these partners, we proposed conduct a field-based experimental study. Specifically, several identical buildings (e.g., houses or condos) will be constructed using traditional methods and several based on the output of our DSS. During this construction, we planned to track a number of outcomes, including time, construction worker and supervisor perceptions, and worker physical exposures.

3. Assessing Physical Demands during Panelized Construction

3.1. Model-based estimates of lumbosacral loads during panelized construction tasks

Jia B, Kim S, Nussbaum MA: [2011] An EMG-based model to estimate lumbar muscle forces and spinal loads during complex, high-effort tasks: development and application to residential construction using prefabricated walls. *International Journal of Industrial Ergonomics* 41:437-446.

Abstract

Residential building construction is moving toward more industrialized construction methods (e.g., use of prefabricated wall or “panels”), yet remains one of highest risk sectors for work-related musculoskeletal disorders. The centralized design process inherent in the use of wall panels offers the potential for proactive control of musculoskeletal risks, consistent with the prevention-through-design (or PtD) philosophy. As part of an ongoing effort to incorporate ergonomics into panel design, estimates of low back loading and injury risk were needed over a range of tasks performed during panelized construction. Here, a free-dynamic, three-dimensional, electromyography-based model was developed to provide such estimates, which was a modification of an earlier, relatively coarser model. Specific modifications included a more detailed representation of lumbar muscle anatomy and contraction dynamics, high-pass filtering of electromyograms to better represent muscle activation levels, and an enhanced calibration procedure through which five model parameters are specified on an individual basis and used to estimate lumbar muscle forces. With these enhancements, the predictive ability of the model was assessed over a wide range of simulated panel erection tasks. Predicted model parameters corresponded well with values reported earlier. Reasonable levels of correspondence were found between measured and predicted lumbosacral moments, though predictive ability varied between tasks and rotation planes.

Nomenclature			
CW	clockwise	L_i	length of i^{th} muscle
CCW	counter clockwise	LBP	low back pain
DSS	decision support system	ILL	iliocostalis lumborum pars lumborum
EF, k_1	EMG-to-force relationship	ILT	iliocostalis lumborum pars thoracis
EMG	electromyography	LTL	longissimus thoracis pars lumborum
nEMG	normalized EMG	LTT	longissimus thoracis pars thoracis
EO	external oblique	MF	multifidus

FL	force-length relationship	MVC	maximum voluntary contraction
FP, k_2	muscle passive components	PCSA	physiological cross-sectional area
FV	force-velocity relationship	RA	rectus abdominis
GTD, k_3	global time delay	S _F &S _E	muscle stress for flexor and extensor
IO	internal oblique	WMSD	work-related musculoskeletal disorders

1. Introduction

Work-related injuries and illnesses pose a continuing threat to the health and well-being of U.S. construction workers and to the productivity of construction firms. Our emphasis here is on residential construction, a large economic activity requiring over 1 million workers in 2006 (Mullins, 2006), and which is projected to grow by ~ 20% in the approaching decade (BLS, 2008c). Residential construction has been recognized as among those sectors having a relatively high prevalence of work-related injuries and illnesses (BLS, 2008a; BLS, 2008b; Schoonover, et al., 2010), with injury rates likely higher than those reported in centralized databases (Lipscomb, et al., 2003a). In this sector, overexertion injuries are the 2nd largest source of direct costs, and more than half of these injuries result from postural and unexpected loads (Lipscomb, et al., 2003a; Lipscomb, et al., 2003b). Modern residential construction can be viewed as a craft-based enterprise driven by a centralized design process, but this design is detached from the actual construction process on site (e.g., method of assembly) and often takes little or no account of the ergonomic impacts on workers (Wakefield, et al., 2001; O'Brien 2002). Modern construction, and to some extent residential construction, is also moving toward increasing pre-fabrication, one example of which is the use of panels (panelized walls) that are increasingly being adopted by residential US. production builders (Wakefield, et al., 2001).

Panels are designed by a central designer based on several criteria (e.g., preferred and maximal lengths), are built in a manufacturing facility, and are then erected by workers on site. This centralized design process yields an opportunity to control the risk of work-related musculoskeletal disorders (WMSDs) early in the project lifecycle, specifically at the design phase. Such an approach is considered to be the most effective way of preventing and controlling occupational injuries and illnesses, and is consistent with the prevention through design (PtD) philosophy (Schulte et al, 2008). PtD has been promoted by a number of investigators and practitioners, and has begun to gain support and/or interest from involved stakeholders (e.g., Hinze and Wiegand, 1992; Hecker, et al., 2004; Schulte, et al., 2008).

Our group has endeavored to implement a PtD approach to panelized construction by developing a decision support system (DSS) that enables panel designers to enhance both ergonomics and productivity at the design phase (Nussbaum, et al., 2009). This is a software-based approach, involving a simulation of the discrete tasks involved with panelized construction. Underlying this is a need to estimate the ergonomic consequences of a given

design, one important aspect of which are the physical demands and risks at the lumbar spine. For all work-related injuries, the trunk is among the most commonly injured body parts, accounting for 32% of total nonfatal occupational injuries and illnesses in construction (BLS, 2008a), and this motivated the current focus on biomechanical modeling of the low back. Further, a preliminary evaluation using the NIOSH lifting equation (Waters, et al., 1994) indicated that wall erection tasks impose substantial risk of low back injury (lifting indexes rarely <1 and often >3). To make the DSS broader and more representative in terms of estimating the influence of alternative design approaches, more refined estimates of low back loading and injury risk are required. Yet, to the authors' knowledge, no previous evidence of such outcomes is available for the broad range of existing panel erection tasks.

Musculoskeletal modeling is an appealing approach to determine the complex internal loads on the lumbar spine borne by the muscles, joints, and soft tissue during diverse work tasks, since there is lack of non-invasive methods to measure *in vivo* muscle forces and internal spinal loads accurately. Over the past several decades, a variety of biomechanical models have been developed to predict internal loads on the lumbar spine. Most contemporary approaches involve multiple muscles, since earlier models (e.g., single-equivalent muscle) do not account for the effects of muscle co-activation. Diverse strategies have been used in multiple muscle models to partition loads among the several muscles included. These strategies include those based on optimization (e.g., van Dieën, 1997), neural networks (e.g., Nussbaum and Chaffin, 1996), stochastic models (e.g., Mirka and Marras, 1993), electromyography (EMG) (e.g., McGill and Norman, 1986; Granata and Marras, 1995; Nussbaum and Chaffin, 1998), and EMG-optimization hybrids (e.g., Cholewicki and McGill, 1994). Excepting those approaches based on EMG, models using the alternative methods typically do not account for either inter- or intra-individual differences in muscle recruitment strategies.

In contrast, EMG-based models inherently account for different recruitment strategies, including diverse levels of muscle co-contraction, both within and across individuals. Several research groups (McGill and Norman, 1986; Granata and Marras, 1993; Granata and Marras, 1995; van Dieën and Kingma, 2005) have developed EMG-based spine models, each of which differs in terms of model complexity, underlying approaches and/or assumptions. Regarding the latter, some approaches have included model parameters that improve performance yet have unclear physiological interpretations or are not specific to individuals. Earlier, we developed a dynamic EMG-based model based on participant-invariant parameters that were specified through a calibration procedure (Nussbaum and Chaffin, 1998). This model, however, included only coarse representations of muscles and was evaluated only for a relatively narrow range of dynamic tasks.

The objective of this study was to extend our original model by incorporating more detailed and complete muscle anatomy, muscular dynamics, and a refined modeling process, to predict trunk muscle forces and low back loads during a wide range of panel erection tasks (such tasks are inherently complex and dynamic). In this paper, the model development process is comprehensively described, and model performance was evaluated using a wide range of panel erection tasks simulated in a laboratory environment.

2. Methods

2.1 Model Development

A three-dimensional, dynamic model of the lumbar spine was developed, incorporating detailed musculature representations, muscle kinematics, and muscle activation dynamics. Surface EMG, trunk kinematics, and individual anthropometry are inputs to the model, which consists of three components: 1) an anatomical model representing muscle geometry and kinematics, 2) an EMG-based muscle model describing muscle force dynamics, and 3) a spine stiffness model quantifying the effects of motion segment passive tissues. When implementing the model, a set of participant-invariant model parameters is obtained from calibration procedures. In the following, each component is described, as well as methods used for calibration and an experiment from which data were obtained to evaluate model performance.

2.2 Anatomical Model

Participant-specific muscle geometry and trunk kinematic were obtained using the AnyBody™ musculoskeletal modeling system (v3.0, repository 7, AnyBody Technology, Aalborg, Denmark). The muscular representation included 16 muscles crossing the lower lumbar region, divided into a group of flexors [internal oblique (IO), external oblique (EO), rectus abdominis (RA)] and a group of extensors [iliocostalis lumborum pars lumborum (ILL), iliocostalis lumborum pars thoracis (ILT), multifidus (MF), longissimus thoracis pars lumborum (LTL), and longissimus thoracis pars thoracis (LTT)]. Deeper torso muscles (e.g., psoas, quadratus lumborum and transverse abdominis) were not included, due to their relatively small contribution to lumbar kinetics (McGill, 1992) and the difficulty in detecting their activity using surface EMG during highly dynamic tasks, although McGill et al. (1996) showed that such activity can be predicted during a limited set of task types.

Each of the represented muscles was sub-divided into multiple functional fascicles, with distinct insertions and origins, replicating the diverse anatomy within each muscle. Thereby, 92 fascicles were included in the anatomical model (MF=24, ILL=8, ILT=16, LTL=10, LTT=14, EO=4, IO=12, RA=4). As in earlier work (McGill and Norman, 1986; Bogduk, et al., 1992; Cholewicki, et al., 1995; van Dieën and Kingma, 2005), fascicles within each muscle were assumed to have equal activation levels. Initial insertions, via points, and origins were defined according to existing evidence (de Zee, et al., 2007), and were scaled based on individual stature and body mass (AnyBody, v3.0). Measured trunk kinematics (described in 2.7) were input to the anatomic model, yielding estimates of the line of action, length, and velocity at each sample instant.

2.3 EMG-based Muscle Model

The current model is a refinement of that described by Nussbaum and Chaffin (1998) and was implemented in MATLAB™ (v7.2, The MathWorks Inc., Natick, MA, USA). In this approach, the force, $F_i(t)$, generated by the i^{th} muscle fascicle at a given time t , was determined on an individual basis and as a function of: normalized EMG ($nEMG$); EMG-to-force relationship (EF ; parameter k_f); muscle stress (maximal force per unit area) for flexors (S_F) and extensors (S_E);

physiological cross-sectional area (PCSA); muscle passive contribution (FP ; k_2); and functional properties [time lag between EMG and measured force (k_3), force-length (FL), and force-velocity (FV) relationships]. As such, a unique model is obtained for each individual, by specifying the five noted parameters during calibration (described in 2.6):

$$F_i(t) = Fmax_i \times [EF(nEMG_i(t, k_{3,i}), k_{1,i}) \times FL(L_i) \times FV(V_i) + FP(L_i, k_{2,i})] \quad (1)$$

where $Fmax_i$ represents muscle strength (i.e., the product of muscle stress and PCSA). L_i represents the length of i^{th} muscle. PCSAs were initialized using values from the literature (Stokes and Gardner-Morse, 1999), and the contribution of PCSA to individual differences in muscle strength was incorporated through specification of S_F and S_E during calibration.

Several modifications to the earlier approach were made: 1) to refine and improve the representation of muscle geometry (as noted above) and functional properties, 2) to specify more efficiently some of the parameters, and 3) to allow the model to be used in more complex, dynamic, and high-effort tasks. The influence of muscle contraction velocity on force generation capability was represented using the FV relationship reported by McGill and Norman (1986):

$$\begin{aligned} FV(V_i) &= (0.9 + 0.25V_i) / (V_i + 0.9) && \text{for } V_i < 0 \text{ (concentric)} \\ FV(V_i) &= 1 + 1.6V_i && \text{for } 0 \leq V_i < 0.125 \text{ (isometric to slow eccentric)} \\ FV(V_i) &= 1.2 && \text{for } V_i \geq 0.125 \text{ (fast eccentric)} \end{aligned} \quad (2)$$

where FV is a scaling factor accounting for the influence of contraction velocity V_i (m/sec) of the i^{th} muscle fascicle on force generation capacity.

The time lag between the onset of EMG and the onset of force production, often referred to as electromechanical delay (EMD), is an important parameter in modeling skeletal muscles (Cavanagh and Komi, 1979; Norman and Komi, 1979). Determination of a muscle-specific EMD, however, is difficult since individual muscles can be rarely isolated; instead, they work together as synergists or antagonists (Ross, et al., 1993; Thelen, et al., 1995; van Dieën, et al., 2003a). In biomechanical modeling, estimates of electromechanical delay (EMD) are usually made by assuming that only measured agonistic muscles are active, and with minimal (or no) antagonistic co-contraction (e.g., Vos, et al., 1990). Here, a new approach was used, the Global time delay (GTD), which accounts for individual recruitment strategies. Given that substantial antagonist and agonist activity was present, this approach was expected to provide an improved estimate of EMD. Measured moments were obtained via inverse dynamics from AnyBody™. Predicted moments were not available at this point (i.e., the EMG-based model was not yet fully specified), and so were indirectly estimated. As such, a weighted summation of $nEMG$, $[\sum (w_i \times$

$nEMG_i$], was used to estimate the total moment contribution of muscles spanning the L5/S1 joint; this estimate is proportional to the predicted moment. Muscle contraction patterns were determined from $nEMG$ and the weighting factors (w_i), representing the maximum moment contribution of each muscle fascicle to the net moment, were calculated as the ratio of maximum contributions of the i^{th} fascicle relative to the total contribution across all muscles:

$$w_i = EMG_{\max,i} (r_i \times f_i) / \sum_i EMG_{\max,i} (r_i \times f_i) \quad (3)$$

where r_i is the position vector of the i^{th} fascicle relative to the L5/S1 rotation center and f_i is a unit vector along the fascicle's line-of-action.

GTD was determined as the time offset that maximized the correspondence (r^2) between measured and predicted triaxial moments at L5/S1 during model calibration (described in 2.6). The average estimated GTD across several maximal efforts was incorporated into the EMG-to-force relationship (as parameter k_3) to account for the time lag between measured force and global muscle activation. Note that the above procedure assumed a linear relationship between EMG and muscular force, which is consistent with earlier evidence (Nussbaum and Chaffin, 1998; Theado, et al., 2007; Brown and McGill, 2008) and our subsequent calibration results. Though a linear EMG-force relationship is recommended to account for muscle co-contraction (Brown and McGill, 2008), further work is needed to allow for potential nonlinearities in the force-EMG relationship during such calibration (as was assumed here), and to account for EMD differences between individual muscles and/or fascicles as well the influence of contraction velocity, initial muscle length, and fiber type composition (Viitasalo and Komi, 1975; Cavanagh and Komi, 1979; Vink, et al., 1989; van Dieën, et al., 1991).

2.4 Spine Stiffness Model

Forces and moments generated by deformation of passive spine elements at L5/S1 were estimated from existing literature. Spine stiffness was obtained from the motion segment stiffness matrix (Panjabi, et al., 1977), with consideration of axial compressive preloads (Stokes and Gardner-Morse, 2003; Gardner-Morse and Stokes, 2004). The spine stiffness contribution (F_{stiff}) at the L5/S1 joint in three orthogonal axes (x , y , z) is expressed as:

$$F_{stiff}(t) = \begin{bmatrix} \gamma_x(t) \\ \gamma_y(t) \\ \gamma_z(t) \\ \mu_x(t) \\ \mu_y(t) \\ \mu_z(t) \end{bmatrix} = \begin{bmatrix} \ddots & & & & & \\ & (c_2(1 - e^{c_1 F}) + K_0) & & & & \\ & & \ddots & & & \\ & & & \ddots & & \\ & & & & \ddots & \\ & & & & & \ddots \end{bmatrix}_{6 \times 6} \begin{bmatrix} \delta_x(t) \\ \delta_y(t) \\ \delta_z(t) \\ \theta_x(t) \\ \theta_y(t) \\ \theta_z(t) \end{bmatrix} \quad (4)$$

where coefficients c_1 , c_2 and the non-preload stiffness K_0 were obtained based on Stokes and Gardner-Morse (2003). F is the axial compressive preload from upper body weight, estimated based on segment mass-center locations and mass distributions as summarized in Chaffin et al. (2006, pp. 37-49). The terms $\delta(t)$ and $\theta(t)$ are the relative intervertebral translation and rotation, respectively, about the L5/S1 joint, and were calculated based on trunk kinematics. Finally, γ and μ respectively represent force and moment generated at L5/S1 by deformation of passive spine elements (i.e., disc, ligaments, facets).

2.5 Spine Force and Moment Prediction

Internal (reactive) spinal forces generated by muscles at the L5/S1 joint (e.g., compression and shear forces) were determined from the vector sum of estimated muscle forces (Granata, et al., 1999; van Dieën and Kingma, 1999). Internal spinal moments, $M(t)$, produced by the 92 muscle fascicles [$r_i \times F_i(t)$] and deformation of passive spine elements (μ) were then obtained as:

$$M(t) = \sum_i^{92} r_i \times F_i(t) + \mu(t) \quad (5)$$

2.6 EMG data collection and model calibration

The bilateral activity of three flexors (IO, EO and RA) and four extensors (MF, ILL, LTL and LTT) were monitored using two telemetered EMG systems (TeleMyo 900, Noraxon, AZ). Pairs of disposable bipolar Ag/AgCl electrodes (AccuSensor, Lynn Medical, MI) with a 2.5 cm inter-electrode distance were placed bilaterally on the skin surface as described by van Dieën (1997) and Potvin et al. (1996). A single pair of electrodes was used to monitor the LTL and ILT on each side (Cholewicki and McGill, 1996; van Dieën, 1996; van Dieën, 1997; Kiefer, et al., 1998; Danneels, et al., 2001b; Coorevits, et al., 2005). This approach was based on previous evidences that ILT and LTL are synergistic and contain similar fiber type distributions (Thorstensson and Carlson, 1987), and prior strategies used to monitor the activations of those muscles (Vink, et al., 1987; Danneels, et al., 2001a; van Dieën, et al., 2003b). Skin preparation involved abrasion and cleaning with a mild alcohol solution, and inter-electrode impedance was verified as $< 10 \text{ K}\Omega$.

Raw EMG signals were collected at 1080 Hz, band-pass filtered (20 - 400 Hz), and subsequently processed using the following steps. First, raw EMG was high-pass filtered using a cut-off frequency of 300 Hz (bidirectional 1st-order Butterworth). High-pass filtering was used as it has shown improvements in the representation of muscle activations (Potvin and Brown, 2004; Staudenmann, et al., 2007; Keenan and Valero-Cuevas, 2008; Brown, et al., 2009). Second, the high-pass filtered EMG signals were rectified. Third, the rectified EMG signals were low-pass filtered at 2 Hz (bidirectional 1st-order Butterworth) to create a smoothed curve more closely matching actual force output (Potvin and Brown, 2004; Staudenmann, et al., 2007). Finally, the processed EMG signals were normalized using individual maximal and minimal values (Mirka, 1991). The former were obtained from maximum voluntary contractions (MVCs) as described below, while minimal values were obtained for the ventral and dorsal muscles in relaxed supine and prone positions, respectively.

Model parameters were specified for each participant, using a set of MVCs and a maximum passive trunk flexion task (*cf.* Nussbaum and Chaffin, 1998). MVCs comprised a set of ramp-up, hold, and ramp-down efforts, during which the participant stood in a custom frame attached to a force platform (Bertec 4550-08, Worthington, OH). Therein, the pelvis and lower legs were securely but comfortably restrained by pelvic, thigh, and knee straps. Participants performed three trials, with one minute of rest between MVCs, for each of six efforts: trunk flexion/extension, right/left lateral bending, and clockwise/counterclockwise axial rotation. Excepting trunk extension, which was done in 20° of trunk flexion, all other efforts were in the upright posture. For the passive flexion task, participants stood on a force platform (AMTI OR6-7-1000, Watertown, MA) with their feet together in fully flexed posture while holding a 6.5 kg mass in their hands, and were instructed to relax their trunk muscles.

Muscle stresses for flexors and extensors (S_F and S_E) and k_1 were determined as a group, using data from the MVCs, through an iterative procedure that minimized lumbar moment differences (measured vs. predicted) in all three rotation planes. Similarly, muscle passive stiffness (k_2) was identified as the value that minimized moment prediction differences during the passive flexion task. All model parameters were established prior to evaluation trials (as described in 2.7) and were held constant thereafter.

2.7 Model Evaluation

The spine model was evaluated using data obtained from an experiment involving simulated residential construction using panelized walls, as part of a larger investigation (Nussbaum et al., 2009). Twenty-four participants (19 male and 5 female) were recruited from the university and local community, and their mean (SD) age, stature, and body mass were 24.2 (4.8) yrs, 174.2 (8.0) cm, and 71.4 (12.8) kg, respectively. All reported being physically active and having no illnesses, injuries, or musculoskeletal disorders within the past year that restricted their daily activities. All participants completed informed consent procedures approved by the Virginia Tech Institutional Review Board.

Following initial measurements, electrode placements, and MVCs, participants performed 10 panel erection trials, which included different types of carrying (C), erecting (E), lifting (L), and moving (M) tasks (Table 1). Each trial was performed under several combinations of panel mass (light vs. heavy, representing unsheathed and sheathed walls) and panel size (small = 1.2 x 2.4 m, medium = 2.4 x 2.4 m, and large = 3.0 x 2.4 m). The set of tasks simulated situations observed in the field (Nussbaum, et al., 2009; Kim, et al., 2011).

Table 1. Summary of simulated panel erection tasks used for model evaluation (see Kim et al., 2011 for further details).

Task	Description	Task	Description
C1	Carrying panel in horizontal orientation	E1KSide	Erecting a panel until it stands vertically with panel initially held at knuckle height and participant standing at panel side
C2	Carrying panel while holding it angled at roughly 45° to the ground	L1G	Lifting a panel horizontally from ground level
E1GTop	Erecting a panel until it stands vertically with panel initially held at ground level and participant standing at the top-plate side of the panel	L1K	Lifting a panel horizontally from an individual's knuckle height level
E1GSide	Erecting a panel until it stands vertically with panel initially held at ground level and participant standing at panel side	L2G	Lifting and titling a panel from 0° to ~ 45° to the floor at the completion of lifting
E1KTop	Erecting a panel until it stands vertically with panel initially held at knuckle height and participant standing at the top-plate side of the panel	M1	Pushing a vertically placed panel forward along long axis

Participants began the trials standing on two force platforms (AMTI OR6-7-1000, Watertown, Massachusetts) with one foot on each. External hand kinetics were monitored using two triaxial load cells (AMTI MC3A-6), placed at self-selected “optimal” locations identified during prior practice trials. EMG, force platform, and load cell signals were collected at 1080 Hz. Whole-body kinematics were recorded using a set of passive reflective markers placed over anatomical landmarks: spinous processes of 7th cervical and 8th thoracic vertebrae and lumbosacral joint, upper and lower arms, lower leg, and heels. Marker data were collected at 120 Hz using a 6-camera system (Vicon 524, Vicon System, Los Angeles, CA). Subsequently, force platform and load cell signals were low-pass filtered with a cut-off frequency of 12 Hz, and marker positions were similarly filtered (cut-off frequency = 9 Hz). EMGs were processed as described in 2.6.

Model performance was evaluated from data obtained in 1070 trials, by comparing measured and predicted triaxial moments at L5/S1. For each trial, comparison of these moments yielded three performance measures in three rotation planes: coefficient of determination (r^2), absolute root-mean-square (aRMS) difference, and relative root-mean-square (rRMS) difference. The first was chosen to assess overall correspondence, while aRMS was used to indicate absolute differences between predicted and measured moments. rRMS was obtained by normalizing aRMS to within-trial peak moment, and was used to represent the quality of model predictions relative to task demands. Lastly, the cumulative distribution function (CDF) of r^2 was derived to summarize results across trials.

2.8 Statistical Analyses

Initially, a multivariate analysis of variance (MANOVA) was conducted to assess the main effects of panel mass, panel size, and erection task on the performance measures (i.e., r^2 , aRMS, and rRMS). Where MANOVA showed a significant effect, a repeated ANOVA was used to identify effects on each rotation plane. Note that only main effects were examined, as the experiment did not include factorial combinations and our primary interests were whether model performance might differ between levels of the individual factors. Throughout, a p -value < 0.05 was considered statistically significant, and all summary data are presented as means (SD). All statistical analyses were performed with JMP 7.0 (SAS Institute Inc., Cary, NC).

3. Results

3.1 Model Calibration

Calibration procedures yielded muscle stress values (S_F and S_E) of 100.5 (44.4) N/cm² for the flexor muscles and 83.2 (39.8) N/cm² for the extensor muscles. Parameters describing the EMG-to-force relationship (k_1), muscle passive contribution (k_2), and time lag (k_3) were 0.34 (0.11), 0.9 (0.4), and 162 (54) ms, respectively. Calibrated models yielded a relatively high correspondence between measured and predicted moments in all three planes (representative results shown in Figure 1). Across all MVC trials aRMS was 3.9 (1.5) Nm, and in the passive flexions trials aRMS was 2.4 (2.0) Nm.

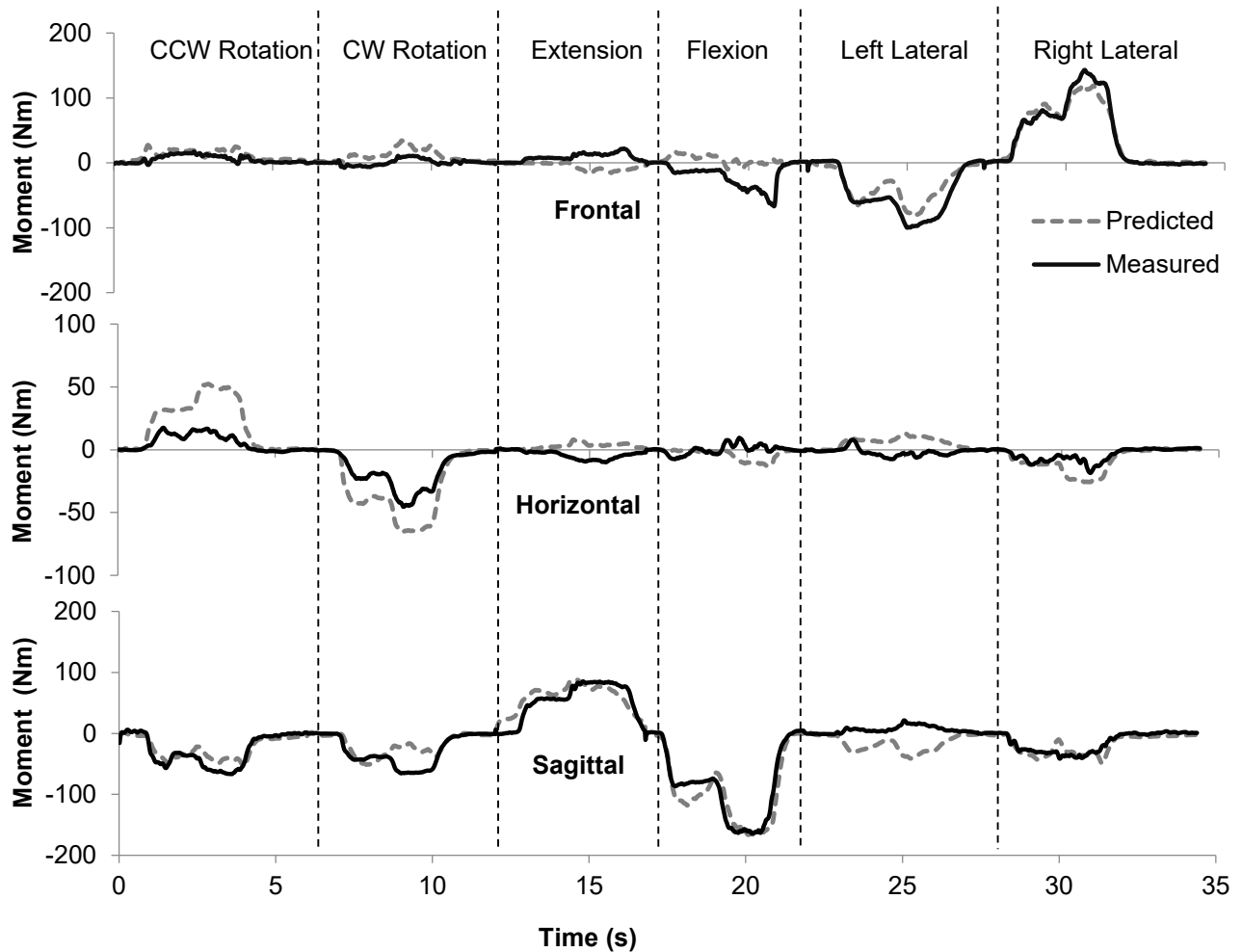


Figure 1. Representative results from model calibration ($S_E = 40 \text{ Ncm}^2$; $S_F = 110 \text{ Ncm}^2$; $k_1=0$; $k_2=1.1$; $k_3=162 \text{ ms}$; $a\text{RMS}=2.72 \text{ Nm}$). Note that all six of the maximal efforts (listed at the top) are concatenated for clarity. Measured external and model-predicted internal lumbar moments are shown in each of the three rotation planes (+ = extension, right lateral bending, and CCW rotation for external moments). Predicted (internal) moments are shown with inverted signs, to facilitate comparisons with external moments.

3.2 Model Evaluation

Predictive ability of the EMG-based model was supported by a high correspondence between measured and predicted moments during the panel erection trials (summary in Table 2, representative results in Figure 2). The CDF of r^2 (correspondence between measured and

predicted moments) indicated that 27, 26, and 50% of trials had $r^2 > 0.8$ in the frontal, horizontal and sagittal planes, respectively, and respective proportions of 12, 10, and 28% with $r^2 > 0.9$.

Table 2. Summary of external moments and measures of model performance (across 1070 experimental trials). The 50th and 95th percentile intra-trial moments, overall correspondence (r^2) between measured versus predicted moments, and absolute (aRMS) and relative (rRMS) moment differences are reported in each rotation plane as means (SD).

	Frontal	Horizontal	Sagittal
50 th ile moment (Nm)	27.3 (12.3)	13.7 (8.7)	109.9 (34.6)
95 th ile moment (Nm)	116.1 (12.9)	104.0 (8.4)	298.4 (34.6)
r^2	0.54 (0.29)	0.51 (0.31)	0.69 (0.26)
aRMS difference (Nm)	6.8 (9.4)	4.8 (5.6)	8.3 (8.0)
rRMS difference (%)	21 (11)	21 (13)	11 (7)

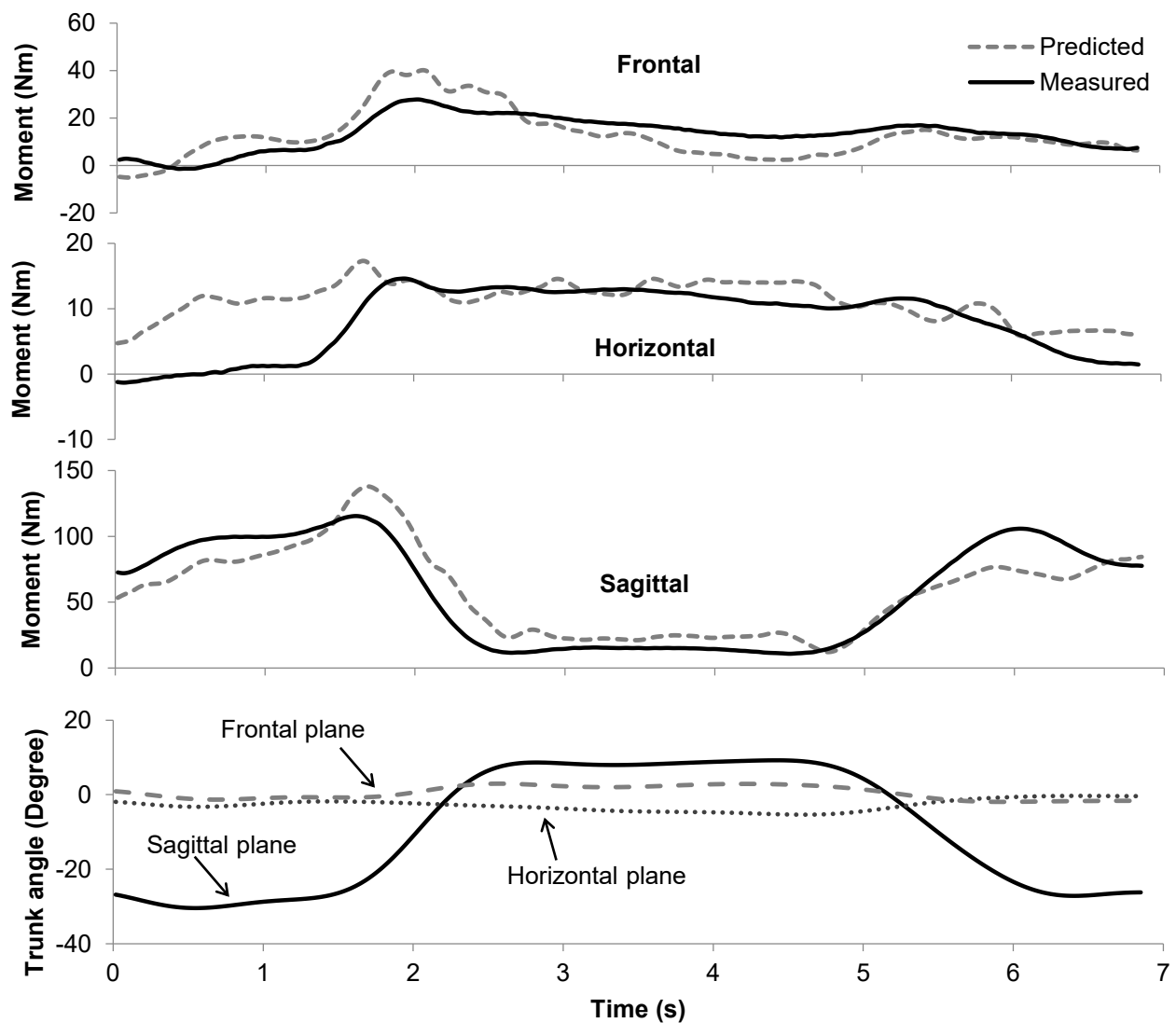


Figure 2. Representative results from a panel lifting task (L1K: $S_E = 45 \text{ Ncm}^2$; $S_F = 60 \text{ Ncm}^2$; $k_1 = 0$; $k_2 = 1.1$; $k_3 = 108 \text{ ms}$). Measured and predicted moments at L5/S1 are shown in the top

three panels for each rotation plane, with trunk angles shown in the fourth panel (+=extension, right lateral bending, and CCW rotation for external moments and torso angles). Predicted (internal) moments are shown with inverted signs, to facilitate comparisons with external moments.

The level of correspondence (r^2) between predicted and measured moments differed across tasks and between the three rotation planes (Figure 3). In the sagittal plane, horizontal lifting tasks (L1G and L1K) yielded the highest values [0.80 (0.16) and 0.77 (0.18), respectively], followed by E1Gtop, E1Gside, and L2G which each had comparable r^2 values. Carrying tasks exhibited relatively poorer levels of correspondence [r^2 for C1 = 0.54 (0.29) and for C2 = 0.59 (0.28)]. In the frontal plane, L2G had the best correspondence [0.65 (0.24)], followed by M1, E1Kside, and E1Gside, and L1G yielded the lowest values [0.36 (0.29)]. In the horizontal plane, the highest r^2 value was 0.73 (0.25) for E1Kside, and the lowest was 0.36 (0.29) for L1G. In general, sagittal plane moments had higher r^2 values than either frontal or horizontal plane moments (Table 2).

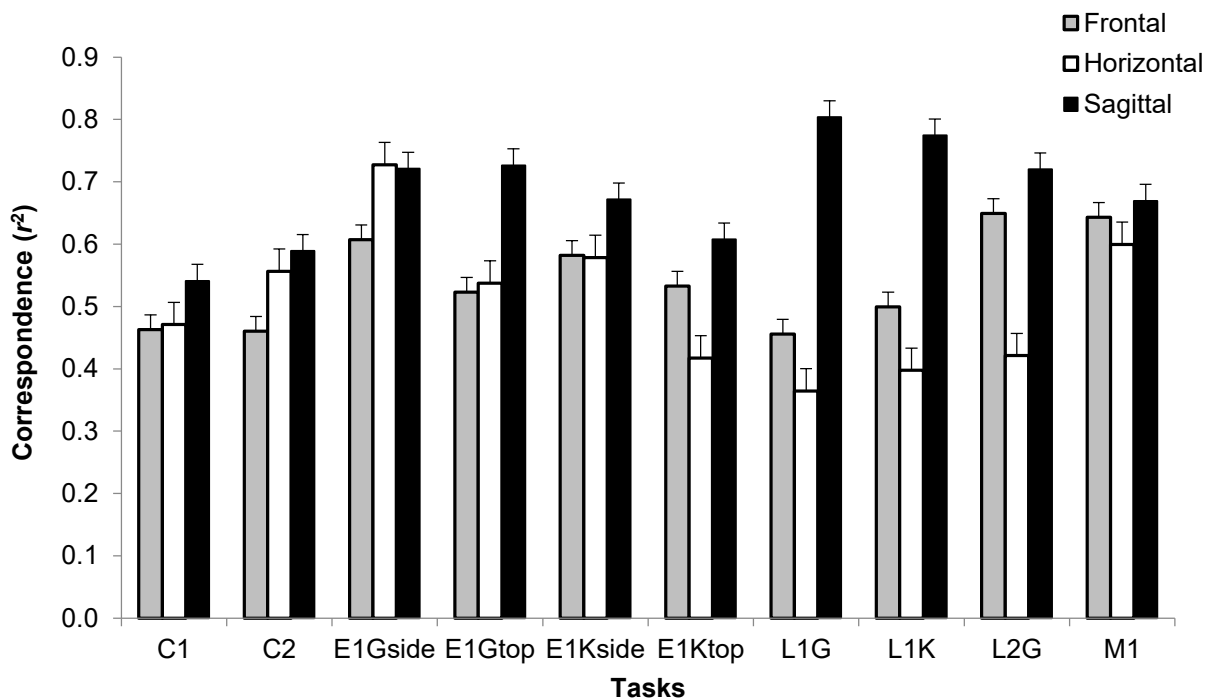


Figure 3. Summary of measures of overall correspondence (r^2) between measured and model-predicted lumbosacral moments. Mean values are shown for each of the panel erection tasks and for each of the rotation planes. Error bars indicate standard errors.

Typical absolute differences between measured and predicted moments (aRMS) were generally largest in the sagittal plane (Figure 4). In the frontal plane, aRMS ranged from 2.6 to 8.3 Nm across all tasks except for E1Kside [15.1 (15.9) Nm]. In the horizontal plane, over half of the tasks resulted had an aRMS difference < 5 Nm. In contrast to aRMS, relative differences (rRMS) were smallest in the sagittal plane (Table 2, Figure 5), and largest in the frontal plane. The largest rRMS differences were found in two lifting tasks (L1G and L2G), while M1 had the lowest rRMS values across the three rotation planes.

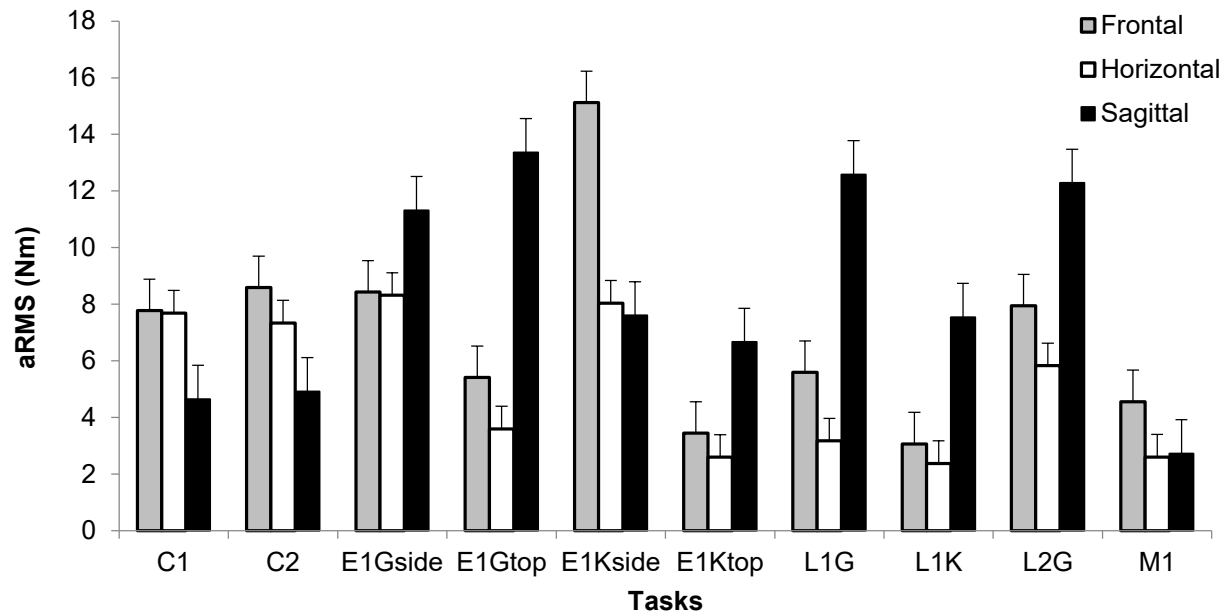


Figure 4. Summary of measures of absolute RMS (aRMS) differences between measured and model-predicted lumbosacral moments. Mean values are shown for each of the panel erection tasks and for each of the rotation planes. Error bars indicate standard errors.

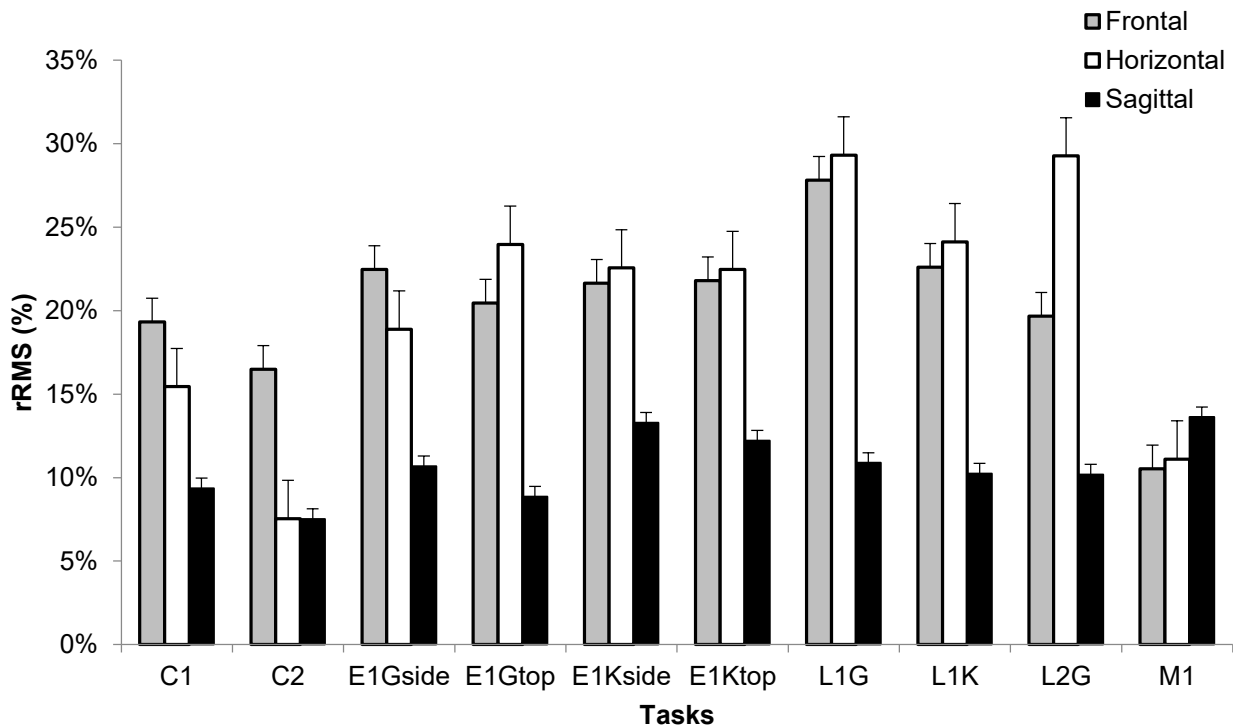


Figure 5. Summary of measures of relative RMS (rRMS) differences between measured and model-predicted lumbosacral moments. Mean values are shown for each of the panel erection tasks and for each of the rotation planes. Error bars indicate standard errors.

Multivariate effects of panel mass, panel size, and panel erection task were each significant (Table 3). Panel erection task also had significant univariate effects on each of the performance measures in all three rotation planes. Panel mass significantly affected aRMS differences in the sagittal plane ($p < 0.01$), with marginally significant effects ($p = 0.05$) in the horizontal and frontal planes. On average, aRMS differences were 12% larger in the heavy vs. light conditions. Panel size had a significant effect only on rRMS differences in the sagittal plane ($p < 0.01$): large [10.6% (7.0%)] = medium [10.8% (6.8%)] < small [12.2% (8.8%)].

Table 3. Summary of effects (F and p values) of panel size, mass, and erection task on measures of model performance: overall correspondence (r^2), absolute RMS (aRMS), and relative RMS (rRMS). Each measure is based on comparisons of measured vs. predicted moments, and effects are indicated in each rotation plane. Significant effects ($p < 0.05$) are in bold.

		Panel size		Panel mass		Panel erection task	
		$F_{(2,1057)}$	p	$F_{(1,1057)}$	p	$F_{(9,1057)}$	p
MANOVA		2.31	<0.01	2.32	0.015	21.96	<0.01
ANOVA							
r^2	Frontal	0.35	0.71	0.45	0.50	6.17	<0.01
	Horizontal	1.86	0.16	0.01	0.97	15.65	<0.01
	Sagittal	1.13	0.32	0.26	0.60	11.36	<0.01
aRMS	Frontal	2.22	0.11	3.84	0.050	25.74	<0.01
	Horizontal	1.57	0.21	3.80	0.052	33.07	<0.01
	Sagittal	1.07	0.36	11.19	<0.01	38.67	<0.01
rRMS	Frontal	2.24	0.11	2.48	0.12	25.04	<0.01
	Horizontal	1.77	0.17	0.01	0.95	29.50	<0.01
	Sagittal	4.57	<0.01	0.01	0.95	8.31	<0.01

4. Discussion

Given the relatively high prevalence of occupational injuries in residential construction, and the need to refine assessments of physical demands and injury risks associated with a variety of construction tasks, the objective of this study was to extend our original model to predict trunk muscle forces and low back loads during a wide range of panel erection tasks (such tasks are inherently complex and dynamic). This new model incorporated more detailed representations of muscle anatomy and contraction dynamics, and is parameterized using participant-specific values obtained through calibration procedures. With these enhancements, the new model was evaluated in terms of predictive ability, and exhibited reasonable levels of correspondence between measured and predicted lumbosacral moments over the wide range of tasks examined.

Models used to estimate low back loads, particularly during complex and dynamic exertions, should adequately account for intra- and inter-individual variability, muscle cocontraction (synergism and antagonism), and muscle physiological properties. In the present approach, five participant-invariant parameters are determined by collectively considering a set of maximal efforts in each rotation plane along with a passive flexion trial. Note that the calibration procedures included multiple MVC tasks in all three rotation planes, which likely elicited values reasonably close to “true” muscle maxima (McGill, 1991). Muscle stresses estimated here (range: $S_F=56\text{-}145\text{ N/cm}^2$; $S_E=43\text{-}123\text{ N/cm}^2$) are comparable to ranges reported in earlier studies: $S_F=40\text{-}140\text{ N/cm}^2$ and $S_E=37\text{-}105\text{ N/cm}^2$ in Nussbaum and Chaffin, 1998; $S=37\text{-}93\text{ N/cm}^2$ in Granata and Marras, 1995; $S=29\text{-}108\text{ N/cm}^2$ in Van Dieën and Kingma, 2005]. The observed range of S_F and S_E values between participants likely indicates that the calibration procedures captured individual differences in muscle stress and PCSA, each of which is difficult to measure directly.

Inter-individual variability in the EMG-to-force relationship (modeled here using k_1) was apparent, in that a linear fit ($k_1 < 0.35$) was obtained for most participants through the iterative estimation procedure yet a nonlinear fit ($k_1 = 1.2$) was identified for three of them. For the latter, use of a linear fit increased RMS differences between measured and predicted moments by ~ 23%. Since parameter k_1 was determined using a diverse set of MVCs, its determination implicitly accounted for the contribution of both agonist and antagonist muscles. Brown and McGill (2008) demonstrated that the EMG-to-moment relationship is more linear than nonlinear if antagonist cocontraction is considered. Further, Staudenmann et al. (2007) indicated that high-pass filtering can enhance the contribution of deeper motor units to surface EMG and result in a relative constant power in the high frequency band (150 – 500 Hz) of EMG signals that could increase the measured activation levels of both agonists and antagonists. Accordingly, the level of cocontraction is likely to be increased, so that the EMG-to-force relationship may become more linear.

Torso flexibility for each participant was modeled by considering intervertebral stiffness and a lumped representation of other passive tissues (using parameter k_2). Relatively large inter-individual variability was found for k_2 [0.9 (0.4)], though these were close to results reported earlier (Nussbaum and Chaffin, 1998). To establish the last model parameter, representing electromechanical delay (k_3), a global time delay (GTD) was introduced. Obtained values [166 (59) ms] were ~30 ms longer than those in earlier work [136.8 (30.9) ms in van Dieën et al., 1991; 132 (27) ms in Nussbaum and Chaffin, 1998], though this discrepancy likely resulted from the current calibration procedures and use of high-pass filtering. Specifically, muscle cocontraction affects the recruitment of different muscle fiber types during a contraction, and hence the onset of measured force output can be altered, which likely changes the time delay (van Dieën, et al., 1991). Staudenmann et al. (2007) further suggested that an increased time delay could be explained by an enhanced contribution of deeper motor units induced by high-pass filtering as used here.

Trunk velocity has been demonstrated to have important effects on predicted spinal loads (Granata, et al., 1999), and muscle force estimation is affected by contraction type (i.e.,

concentric and eccentric) and contraction velocity (Bigland and Lippold, 1954; Raschke and Chaffin, 1996). The current model, in contrast to our earlier approach, included an explicit force-velocity relationship (Eq. 2). This was done to improve predictive ability, as the tasks under investigation were relatively dynamic (i.e., compared to the tasks for the which the earlier model were used). The current work was not intended to rigorously investigate the effects of including a force-velocity relationship on model performance. However, a separate investigation indicated that including the force-velocity relationship significantly and substantially improved predictive ability of the model.

In practice, the panelized construction process includes a variety of tasks as well as different panel masses and sizes. Hence, in the context of our decision support system, model predictions are needed over a wide spectrum of trunk kinematics and muscle activities. Overall, predictive ability of the current model appeared reasonable for the common panel erection tasks and panel design factors (masses and sizes) examined here. Values of r^2 for sagittal plane moments are comparable with those reported in earlier studies (Granata and Marras, 1993; Nussbaum and Chaffin, 1998; Kingma et al., 2001), though the current work examined tasks that were generally more complex and involved a wider variety of kinematics and kinetics. Values for frontal and horizontal plane moments are higher than reported for our earlier model (Nussbaum and Chaffin, 1998), but lower than in some studies (Granata and Marras, 1995; Marras and Granata, 1995). The latter discrepancy may be due to the relatively higher complexity and variety studied here.

Across all experimental trials, the current model yielded somewhat better levels of correspondence (r^2) between measured and predicted lumbosacral moments in the sagittal plane than in other two planes (Table 1). Predictive ability was unaffected by either panel size or mass, but did differ between tasks (Table 2). These differences in predictive ability are, at least in part, explained by trunk dynamics. Depending on both the initial and the final location of a panel and the task type, trunk motions were primarily within one rotation plane (i.e., principle rotation plane), though some conditions involved more substantial motions within this principle plane. Values of r^2 were higher within the principle rotation plane than in the other planes (subordinate rotation planes), perhaps because both external moments and EMG signal-to-noise ratios were larger in the principle rotation plane.

As was the case for overall correspondence between measured and predicted moments (r^2), magnitudes of typical absolute (aRMS) and relative (rRMS) differences were also comparable to those in earlier reports. In previous studies (Cholewicki, et al., 1995; Granata and Marras, 1995; Nussbaum and Chaffin, 1998; Gagnon, et al., 2001; Kingma, et al., 2001), aRMS ranged from 10 to 23 Nm in the frontal plane, 9 to 19 Nm in the horizontal plane, and 18 to 52 Nm in the sagittal plane. Somewhat lower respective mean values found here: 6.8, 4.8 and 8.3 Nm. In addition, aRMS differences increased significantly with panel mass in all three rotation planes. This effect may have resulted from increases in torso muscle activity with increasing panel mass. As suggested above, there were likely subsequent influences on the magnitude of lumbosacral moments and EMG signal-to-noise ratios. Mean relative (rRMS) differences between measured and predicted moments were 21%, 21% and 11% in the frontal, horizontal

and sagittal planes, respectively. The only available comparison data were by Granata and Marras (1995), who reported similar values in the frontal (24%) and sagittal (15%) planes.

As a whole, the comparisons given above suggest that the present model has at least comparable predictive ability to earlier approaches. In terms of absolute predictions errors, however, the current approach appeared somewhat more effective, though it remains to be determined what measures best indicate model performance (e.g., in terms of predicting internal spinal loads). Further, the range of tasks studied here were both more diverse (range of external moments and rotation planes in which these were present) and more complex (external moments at substantial levels in multiple rotation planes simultaneously) than those with which other modeling approaches have been evaluated.

A few limitations in the present work should be acknowledged. First, the current model includes only one motion segment (i.e., L5/S1). Arjmand et al. (2007) showed that estimated muscle forces vary with spinal level if a model considers only a single level, and that muscle forces estimated this way violate equilibrium at remaining spinal levels. Second, consistent with earlier modeling approaches, EMG normalization was done using data obtained in a posture that was not always consistent with postures in which the model was used. Here, maximal EMG values were obtained during MVCs conducted in specified postures (mostly upright), yet the panel erection tasks often involved substantial trunk motions. Since maximal EMG values vary with posture and influence normalized values (Mirka, 1991), this is a likely a non-trivial source of error. Short of an intensive preliminary data collection to obtain maximal EMG values over a range of postures, additional work is needed to address this issue. Third, interpretations based on model predictions in subordinate planes require some caution since these predictions seemed somewhat inferior. Better measurements of trunk kinematics, more precise representations of individual muscular anatomy, and methods to account for inaccessible (deep) muscles may, in the future, help improve model predictive ability.

In summary, a free-dynamic three-dimensional EMG-based biomechanical model has been developed to predict low back loads under various dynamic tasks. Through a calibration procedure, five model parameters are specified on an individual basis and used to estimate lumbar muscle forces. This model was assessed during a range of common panel erection tasks, and demonstrated a reasonable level of predictive ability. Subsequently, model outputs (e.g., internal spinal loads and muscle forces) will be used as quantitative descriptions of the physical demands and injury risks placed on construction workers during these tasks, which will be incorporated into our ongoing efforts to facilitate proactive design of residential construction using panelized walls. Additional work is underway to investigate effects of panel erection tasks on trunk kinematics and low back loads (e.g., Jia et al. 2009), and the correspondence between trunk kinematics and low back loads will be identified. Further research is still needed, however, to improve predictive ability and to extend the model to multiple spinal levels.

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3.2. Low back injury risks during panelized construction tasks

Kim S, Nussbaum MA, Jia, B: [2011] Low back injury risks during construction with prefabricated (panelised) walls: effects of task and design factors. *Ergonomics* 54:60-71.

Abstract

New technology designed to increase productivity in residential construction may exacerbate the risk of work-related musculoskeletal disorders (WMSDs) among residential construction workers. Of interest here are panelized (prefabricated) wall systems (or panels), and facilitating an ongoing effort to provide proactive control of ergonomic exposures and risks among workers using panels. This study, which included 24 participants, estimated WMSD risks using five methods during common panel erection tasks and the influences of panel mass (sheathed vs. unsheathed) and size (wall length). WMSD risks were fairly high overall; e.g., 34% and 77% of trials exceeded the “Action Limits” for spinal compressive and shear forces, respectively. Heavier (sheathed) panels significantly increased risks, though the magnitude of this effect differed with panel size and between tasks. Higher levels of risk were found in tasks originating from ground vs. knuckle height. Several practical recommendations based on the results are discussed.

1. Introduction

Although there have been recent declines, construction workers continue to experience a relatively high number of injuries and illnesses requiring days away from work, accounting for 11% of total nonfatal occupational cases requiring days away from work (BLS, 2009). In addition, a 4.5-year follow-up study among carpenters and pavers showed that regular use of ergonomic measures remained low despite a large educational campaign at the sector level. Within the construction sector, residential carpenters in particular have relatively high rates of morbidity, and overexertion has been identified as a major causal factor (Dement & Lipscomb, 1999; Lipscomb, Dement, & Behlman, 2003; Lipscomb, Dement, Li et al., 2003). More specifically, overexertion injuries appear to be associated with manual handling of construction materials. For example, overexertion was the 2nd most costly injury cause, and costs associated with overexertion largely resulted from lifting framed walls and setting steel beams (Lipscomb, Dement, & Behlman, 2003).

Public and private efforts are being made to improve technology in housing with an emphasis on reducing work-related injuries and illnesses and increasing productivity and efficiency (National Association of Home Builders Research Center, 2000, 2002). Panelized wall systems (i.e., use of panelized walls or panels) are an example of such technology, and which is increasingly being adopted by residential U.S. production builders (Wakefield et al., 2001). Panels are manufactured in a factory under controlled environments with material handling systems and/or assistive devices. As such, off-site production provides opportunities to reduce hazard levels, construction time and cost, the need for skilled and experienced workers on site, etc. (Toole, 2001; Toole & Gambatese, 2008).

Despite such potential benefits, panels typically are designed without considering the workers who will actually handle them, and as a result workers may be exposed to increased levels of ergonomic risks while handling panels due to their masses, sizes, changes in work process, etc. A panelization design, or set of panels for a given structure, is developed from an architectural plan using a centralized design process involving a panel designer. These panel designers generally do not perceive the ergonomic effects of panel designs on construction workers, and make design decisions largely based on transportation and panel stacking issues (Kim et al., 2008). Given that there is a centralized design aspect, and the potentially broad “downstream” impacts possible at this level, our group is employing the prevention-through-design (PtD) philosophy to develop a decision support system (DSS) that will allow panel designers to proactively address ergonomic concerns (Nussbaum et al., 2009). Note that PtD has been promoted and accepted as an effective way to “design out” hazardous exposures from the workplace (e.g., Gambatese et al., 2005; Gambatese & Hinze, 1999; Schulte et al., 2008).

Required for this DSS are quantitative descriptions of ergonomic exposures and risks for panel erection tasks in relation to panel design factors (e.g., mass and size). Such data are needed to evaluate the ergonomic effects of alternative panel designs, panel stacking and erection methods, etc. However, to the authors’ knowledge, no such formal assessments have been performed on panel erection tasks. The focus of the current work is thus to obtain risk assessments, the quantitative or qualitative value of risk associated with a given task condition. A primary emphasis was on the risk of a low back disorder. Such morbidity is relatively common in residential construction (Dement & Lipscomb, 1999; Fredericks et al., 2005; Lipscomb et al., 2009), and workers who use panels reported this as the body part most likely to be injured (Nussbaum et al., 2009). We hypothesized that panel design factors would affect risk levels during several common panel erection tasks, and specifically that the magnitude of these design factor effects would vary between tasks. Quantifying these effects was anticipated to aid in future panel design efforts, and more specifically to facilitate an assessment (e.g., using the DSS) of the tradeoffs involved in alternative design approaches.

2. Methods

A convenience sample of 24 participants (19 males and 5 females) was recruited from the university and local community, whose mean (SD) age, stature, and body mass were 24.2 (4.8) yrs, 174.2 (8) cm, and 71.4 (12.8) kg, respectively. All participants reported being physically active and having no illnesses, injuries, or musculoskeletal disorders within the past year that limited their daily activities. Participants completed three sessions. In the initial session, they watched a video recording of construction workers performing panel-handling tasks. They also confirmed, by handling panels in the lab, that they felt physically capable of completing the experimental tasks. Two experimental sessions were then completed, at least two days apart. Prior to participation, all participants completed informed consent procedures approved by the Virginia Tech Institutional Review Board.

2.1. Experimental design and procedures

A set of biomechanical, physiological, and psychophysical measures were obtained in a balanced incomplete block design with block size = 2. Three independent variables (IVs) were experimentally manipulated: panel *Size* [small (1.2 m x 2.4 m), medium (2.4 m x 2.4 m) and large (3 m x 2.4 m)], panel *Mass* [unsheathed (light) vs. sheathed (heavy)], and *Task* type (eight levels, involving lifting, erecting, carrying, and moving). The small panel masses were 30 kg and 53 kg, respectively, for the light and the heavy condition, with corresponding values of 44 kg and 87 kg for the medium panel, and 54 kg and 108 kg for the large panel. These IVs and their levels were determined as representative of the most common activities based on extensive field and video observations (see Nussbaum et al., 2009). The tasks examined are illustrated in Figure 1 and were defined as follows:

- Two levels of lifting type L1: Lift panel horizontally. Panel initially placed on the ground (L1G) or at a participant's knuckle height (L1K) using jack stands. L1G is completed at standing knuckle height. L1K is completed when the panel is raised to a level that it can be carried away from the supporting stands (this was typically midway between knuckle and the elbow heights), which simulated lifting a panel off of a panel stack.
- Lifting type L2G: Lift panel off the floor. L2G is completed with the panel oriented at ~ 45 degrees to the group and with the participant in the upright standing position
- Four levels of erecting E1: Erect panel from ground until it stands vertically while participant stands at panel top-plate (E1GTop) or side (E1GSide), or erect panel from knuckle height while participant stands at panel top-plate (E1KTop) or side (E1KSide).
- Carrying type C1: Carry panel ~3 meters in a horizontal orientation. Panel is held in the final position of L1G.
- Carrying type C2: Carry panel ~ 3 meters while holding it oriented ~ 45 degrees to the ground. Panel is held in the final position of L2G.
- Moving M1: Push vertically-oriented panel forward along bottom edge for ~ 1 meter.

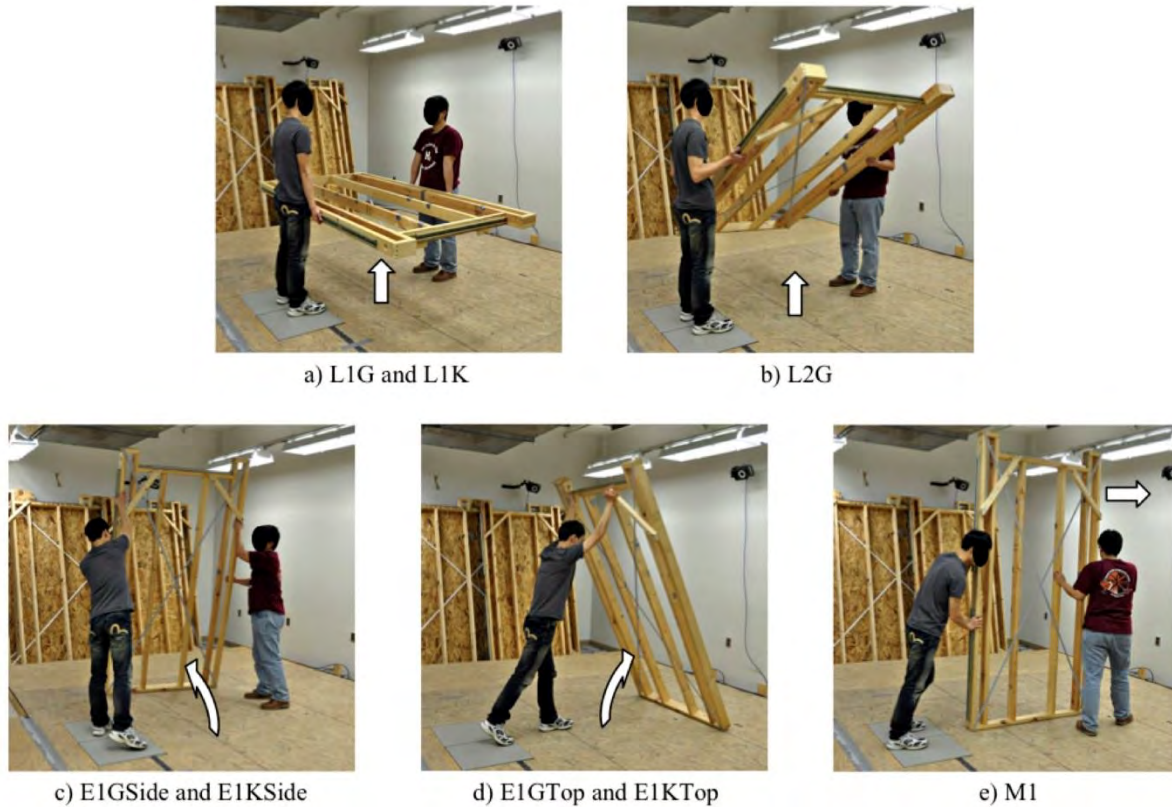


Figure 1. Illustrations of task types. The letters G and K respectively indicate origin at the ground or individual knuckle height. The white arrows indicate the direction of panel movement. Note that carrying panel at the final position of L1G (a) or L2G (b) is C1 or C2.

Each experimental session lasted ~3 hours and involved a different panel size. Participants completed two sessions with a different panel size in each, and each session involved all combinations of Mass and Task (Table 1). A slightly different set of tasks was used for the small panel vs. the medium and large panels (Table 1); some combinations of tasks and panel size were not included as they were very rarely observed in the workplace. Trial order (i.e., combinations of IVs) was controlled such that the order of panel size was first counterbalanced, following the balanced incomplete block design. Then, for the given panel size, the order of panel mass was counterbalanced, and the order of task type was randomized within each panel mass. Each trial lasted ~10 – 20 seconds, and was replicated twice with ~ 2 min rest between trials.

Table 1. Overview of balanced incomplete block design (block size = 2; P# = participant identifier).

Task	Small		Task	Medium		Task	Large	
	Heavy	Light		Heavy	Light		Heavy	Light
L1G	P1 & P2		L1G	P1 & P2		L1G	P5 & P6	

L1K	P3 & P4	L1K	P3 & P4	L1K	P7 & P8
L2G	P9 & P10	E1GTop	P5 & P6	E1GTop	P9 & P10
E1GTop	P11 & P12	E1GSide	P7 & P8	E1GSide	P11 & P12
E1KSide	P13 & P14	E1KTop	P13 & P14	E1KTop	P17 & P18
M1	P15 & P16	E1KSide	P15 & P16	E1KSide	P19 & P20
C1	P21 & P22	M1	P17 & P18	M1	P21 & P22
C2	P23 & P24	C1	P19 & P20	C1	P23 & P24

The number of “workers” was determined from field observations, and depended on the levels of Size, Mass, and Task. For the small panel, one or two were involved: one for the E1GTop and M1 tasks in the light condition and two in the heavy condition. When handling the medium panel, one worker was involved for the E1GTop and E1KTop tasks in the light condition, two for the remaining tasks in the light condition, and three in the heavy condition. For the large panel, two workers were used in light condition and three in the heavy condition. Experimenters (including the authors) served as additional workers.

2.2. Instrumentation

Trials began with participants standing with each foot on a separate force platform (AMTI OR6-7-1000, Watertown, Massachusetts). Practice trials were completed for the given task, and participants indicated their preferred hand positions (inter-hand spacing) on the panel. At these positions, two load cells (AMTI MC3A-6) were attached to collect tri-axial hand forces. During each trial, force platform and load cell signals were sampled at 1080 Hz. These were subsequently low-pass filtered (12 Hz cutoff; 2nd order Butterworth; bidirectional).

Muscle activity was monitored using surface electromyography (sEMG). Pairs of pre-gelled, bipolar, Ag/AgCl electrodes (AccuSensor, Lynn Medical, MI) with a 2.5 cm inter-electrode spacing were placed bilaterally over eight accessible muscles crossing the lower lumbar region: internal oblique, external oblique, rectus abdominis, iliocostalis lumborum pars lumborum, latissimus dorsi, multifidus, longissimus thoracis pars lumborum, and longissimus thoracis pars thoracis. Before electrode placement, the skin was shaved, lightly abraded, and cleaned with 70% isopropyl alcohol; inter-electrode impedance was verified as < 10 KΩ. Electrode placement followed existing protocols (Potvin et al., 1996; van Dieën, 1997). sEMG signals were obtained using two 8-channel telemetered systems (Telemetry 900, Noraxon, Scottsdale, AZ), and sampled at 1080 Hz. Prior to the experimental trials in each session, initial procedures were completed to calibrate an EMG-based model (Nussbaum and Chaffin, 1998; Jia et al., submitted). These included measures of resting and maximal sEMGs and a passive trunk flexion (i.e., full trunk flexion with relaxed trunk muscles).

Body-segment positions and orientations were monitored using passive markers attached bilaterally or in the mid-sagittal plane over several anatomical landmarks: calcaneus, 2nd and 5th metatarsal heads, lateral and medial malleoli, lateral and medial tibial epicondyles, acromial processes, lateral and medial humeral epicondyles, radialis and ulnar styloid processes, the spinous processes of the 7th cervical (C7) and 8th thoracic (T8) vertebrae, incisura jugularis,

xiphoid process (XP), and anterior and posterior iliac superior spines. In addition, clusters of 2 – 4 markers were placed midway between C7 and T8, over the lumbosacral joint, and on the lower legs, upper arms, lower arms, and heels. Marker data were collected at 120 Hz using a 6-camera system (Vicon 524, Vicon system, Los Angeles, CA), and subsequently low-pass filtered (9 Hz cutoff; 2nd order Butterworth; bidirectional).

Selected anatomical markers were removed prior to the panel handling trials, after being referenced to corresponding clusters. Removed markers were reconstructed using clusters on the corresponding body segments (Challis, 1994). The joint coordinate system for each segment was defined, in large part, based on International Society of Biomechanics recommendations (ISB, 2002; Wu & Cavanagh, 1995; Wu et al., 2005), and joint angles were calculated using the Z-X-Y sequence of Euler angles. Derived joint angles were low-pass filtered (5 Hz cutoff; 2nd order Butterworth; bidirectional). For the carrying tasks (C1 and C2), lower extremity angles were not calculated due to loss of marker data. All off-line data processing was completed using Matlab 7 (MathworksTM Inc., Natick, MA).

2.3. Risk assessments

Five methods were used to assess the relative risk posed during common panel erection tasks. These specific methods were selected for relevance to the current tasks and to ensure a reasonably diverse approach to risk assessment. We also sought tools that provided assessments of low back disorder risk. Each method is summarized below.

2.3.1. Spinal loads

A free-dynamic three-dimensional EMG-based model (Jia et al., submitted) was used to estimate muscle and passive tissue forces. This model was based on an earlier approach (Nussbaum and Chaffin, 1998), but included more detailed representations of lumbar muscle anatomy, using the AnyBodyTM modeling system (v3.0, repository 7, AnyBody Technology, Denmark), and muscle contraction dynamics. Participant-specific parameters (of which there are five) were determined through calibration procedures. Values of participant-specific parameters were comparable to earlier studies (e.g., Granata and Marras, 1993; Nussbaum and Chaffin, 1998), and detailed values are reported in Jia et al. (submitted). Normalized sEMGs were used to estimate muscle forces, which were then combined with postural and resultant (external) kinetics to predict lumbosacral (L5/S1) reaction kinetics (i.e., compression and shear forces). The revised model exhibited reasonable levels of the predictive ability during the panel erection tasks examined here (Jia et al. submitted). Within each panel handling trial, 95th percentile (max) compressive and shear forces were determined; these were normalized to individual body weight (Hof, 1996) and the normalized values were used for statistical analyses.

2.3.2. Lumbar injury risk model

The multiple logistic regression model of Marras et al. (1993) was used to estimate the probability of membership in a group at high risk of a low back disorder (P_{Risk}). This model

includes five factors describing trunk motion and workspace factors: lift rate, average twisting velocity, maximum L5/S1 moment, maximum sagittal flexion, and maximum lateral velocity. To obtain trunk kinematics, the lumbar segment was defined from T8, the xiphoid process, and the lumbosacral joint center according to Dumas et al. (2007) and was expressed with respect to the pelvic segment. Then, the angular velocity of the lumbar segment was calculated following the ISB recommendations. Although developed for manufacturing tasks, the model was assumed relevant here as the current tasks also involved lifts, pushes, etc. In each trial, the maximum L5/S1 moment was determined from inverse dynamics using AnyBodyTM. Lift rate was conservatively set to 12 lifts/hr; of note, the risk model is relatively insensitive to lift rate (smallest coefficient).

2.3.3. Lifting Assessment

The revised NIOSH lifting equation (Waters et al., 1994; Waters et al., 1993) is a well-known analytical tool designed specifically to assess injury risks during two-handed manual lifting tasks. Marker positions and load cell data, only from trials involving lifting (L1G, L1K and L2G), were used to determine the recommended weight limit (RWL) and the lifting index (LI). Throughout these analyses, the frequency multiplier was set to 1; from field observations, lifting frequency was typically below 2/min and the duration of lifting tasks was short. The coupling type was set to fair.

2.3.4. Postural Assessment

The Rapid Entire Body Assessment tool (REBA: (Hignett & McAtamney, 2000) was used to assess whole body postures. This tool considers most major body parts (trunk, neck, legs, upper arms, lower arms and wrists) using a scoring system that associates postures with numerical values, similar to the related Rapid Upper Limb Assessment (McAtamney & Corlett, 1993). Using joint angles and load cell data from each trial, a REBA score was obtained at every 10% of the trial duration. Neck and wrist angles were not monitored during the experiment, hence scores for the neck and the wrist were conservatively set to be = 1. In addition, for carrying tasks, the leg score was set to be = 2 by assuming that knee flexion angles were 30° – 60°. The maximum REBA score within each trial served as a dependent variable.

2.3.5. Perceptual Ratings

After completing the two replications of each task, participants provided ratings of perceived exertion (RPE) for the whole body (RPE_{WB}) and lower back (RPE_{LB}). Ratings were obtained using Borg's CR-10 scale (Borg, 1990). This instrument is a 10-point category scale, and was provided along with a human body schematic with graphical descriptors anchored at selected body regions.

2.4. Statistical analyses

Since an incomplete factorial design was used (i.e., not all tasks were done for all panel sizes), a two-phase analysis approach was used. In the first, the analysis focused on the subset of six tasks that were performed with each panel size (Table 1). For these, repeated measures analyses of variance (RANOVA) were used to evaluate the effects of the three IVs (Mass, Size, and Task) on each of the risk assessment measures. The second was a complementary assessment of the alternative tasks that are specific to the panel sizes, and was performed separately for corresponding panel sizes. Specifically, for the small panel size, separate RANOVAs were performed with the following IVs: Mass and Task (L1G, L1K, L2G, C1 and C2). For the medium and large panel sizes, RANOVAs were performed with three IVs: Mass, Size, and Task (E1GTop, E1GSide, E1KTop and E1KSide). The levels of Task were included to provide information not available from the first analysis (which involved only the tasks common to all three panel sizes). Normalized spine loads and LIs were log-transformed prior to statistical analyses to achieve normally distributed residuals, though summary statistics are presented below in the original units. Significant effects were followed by post-hoc pairwise comparisons (Tukey's HSD or Student's *t* tests), and significant interaction effects were further examined using simple effect analysis. In these, the focus was on alternatives within a given task type (e.g. L1G vs. L1K, or panel mass/size within a specific task) as such differences represent potentially modifiable aspects of the panelized construction process. All statistical analyses were performed using JMP 8.0 (SAS Institute Inc., Cary, NC), and statistical significance was determined when $p < 0.05$. All summary data are presented as means (SD) in original units.

3. Results

Overall, the panel erection tasks examined here resulted in fairly high levels of musculoskeletal injury risk. Mean (SD) shear and compressive forces were 885 (478) and 3073 (1268) N, respectively. Shear forces exceeded the "Action Limit" of 500 N suggested by McGill et al., (1998) in 77% of trials, while the corresponding limit for compression of 3400 N (NIOSH, 1981) was exceeded in 35% of trials. Mean (SD) P_{Risk} was 51% (38%), and 28% and 47% of trials had $P_{\text{Risk}} > 90\%$ and 50%, respectively. LI values had a mean (SD) of 2.0 (0.7), and 8% and 94% of lifting trials had LI > 3 and 1, respectively. With respect to REBA scores, the mean (SD) was 7.9 (2.3), and 50% and 18% of trials were at high (> 8) or very high (> 11) risk levels, respectively. In contrast, perceived exertion was relatively low, with participants reporting weak to moderate levels of exertion.

3.1. Effects of Mass, Size, and Task

RANOVA results for all risk assessment measures are summarized in Table 2 (recall that these were based on the subset of six tasks common to all panel sizes). Regarding spine loads, antero-posterior shear (F_x), compression (F_y) and lateral shear (F_z) forces were significantly higher in the heavy vs. light condition [F_x : 901 (446) N > 807 (497) N; F_y : 3215 (1256) N > 2870 (1252) N; F_z : 175 (227) N > 148 (198) N]. There were significant Size x Task interaction effects on F_x and F_y (Figure 2). Lateral shear force was significantly affected by panel Size [Medium > Large $\approx$ Small] and Task [C1 > E1GTop $\approx$ L1G $\approx$ E1KSide $\approx$ M1 > L1K].

Table 2. RANOVA results [*F* value (*p*)] for effects of Mass (M), Size (S), and Task (T) on risk measures. Results are highlighted in bold if significant.

	Mass	Size	Task	M x S	M x T	S x T	M x S x T
AP shear force (F _x)	9.00 (0.0028)	1.01 (0.36)	47.38 (<0.0001)	0.28 (0.75)	2.08 (0.067)	2.62* (0.0041)	0.97 (0.47)
Compression force (F _y)	25.99 (<0.0001)	3.64 (0.0027)	108.00 (<0.0001)	0.44 (0.64)	1.61 (0.16)	2.90** (0.0016)	0.83 (0.60)
Lat. shear force (F _z)	6.33 (0.012)	4.96 (0.0083)	20.97 (<0.0001)	2.02 (0.13)	0.88 (0.49)	0.70 (0.73)	1.16 (0.32)
P _{Risk}	34.2 (<0.0001)	4.62 (0.017)	818.2 (<0.0001)	0.99 (0.37)	5.39 (<0.0001)	5.16 (<0.0001)	0.8 (0.63)
LI	80.38 (<0.0001)	39.43 (<0.0001)	233.26 (<0.0001)	13.12‡ (<0.0001)	9.39‡ (0.0026)	1.23 (0.29)	1.23 (0.29)
REBA	7.17 (0.0077)	1.01 (0.36)	245.33 (<0.0001)	1.4 (0.25)	4.54 (0.0005)	3.50 (0.0002)	3.27 (0.0004)
RPE _{LB}	39.31 (<0.0001)	1.23 (0.29)	32.00 (<0.0001)	1.02 (0.36)	1.13 (0.34)	2.43 (0.0093)	0.18 (1.00)
RPE _{WB}	51.65 (<0.0001)	0.96 (0.38)	26.98 (<0.0001)	0.61 (0.54)	0.44 (0.82)	2.82 (0.0025)	0.21 (1.00)

- *: Effects of Size are significant for all tasks except L1G and M1.
- **: Effects of Size are significant for all tasks except L1G and L1K.
- ‡: Effects of Mass are significant for all tasks.

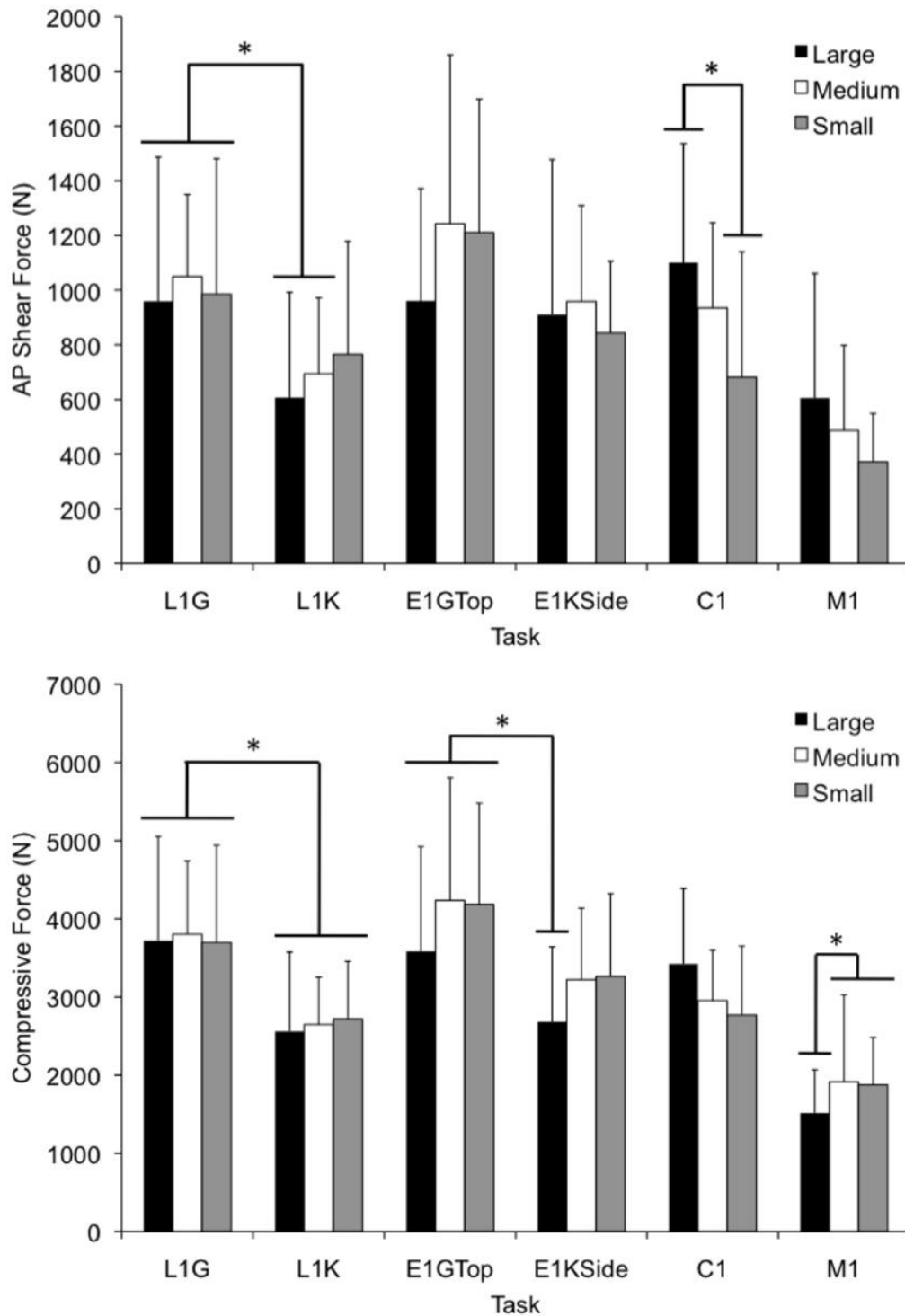


Figure 2. Panel Size x Task interaction effects on anterior/posterior (AP) shear (top) and compressive forces (bottom). Significant differences between panel sizes within the same task type are indicated by *, and error bars indicate standard deviations.

The probability of high-risk group membership (P_{Risk}) was significantly affected by Mass, Size, and Task. Further, Mass x Task and Size x Task interaction effects were both significant and had comparable effects on P_{Risk} , with higher probabilities found for L1G and E1GTop compared to other tasks (e.g., Figure 3). Only the E1KSide task was significantly affected by Mass (Heavy > Light) and Size (Medium = Large > Small).

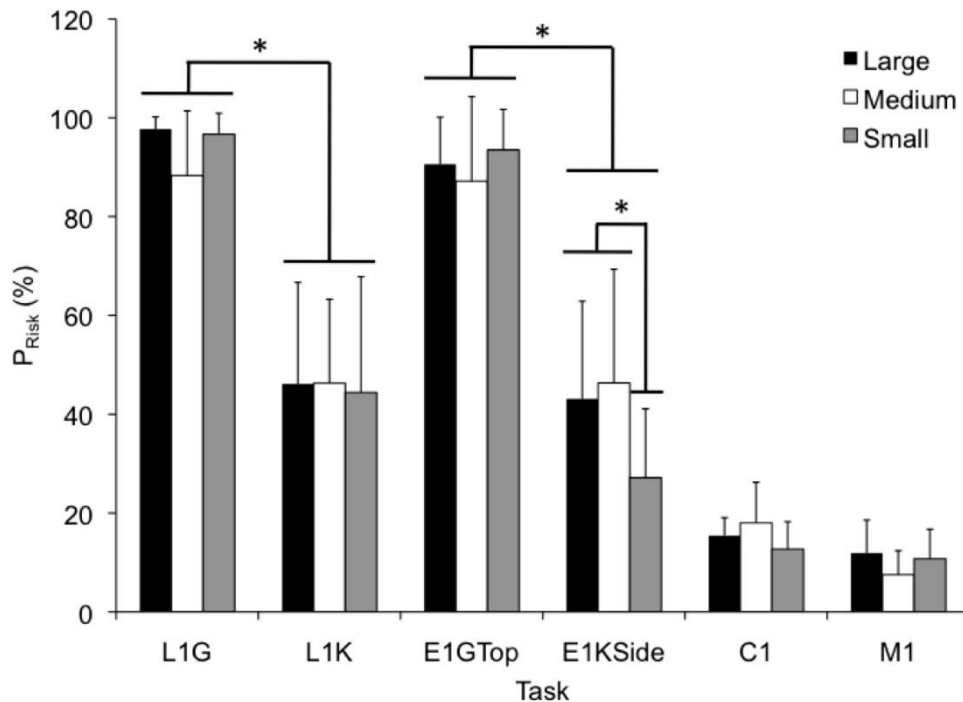


Figure 3. Panel Size x Task interaction effects on the probability of high-risk group membership (P_{Risk}). Significant differences between panel sizes within the same task type are indicated by *.

LIs were significantly affected by several main and interaction effects of Mass, Size, and Task (Table 2). The small and the medium panels yielded larger LI values for the heavy vs. light condition [Small: 1.8 (0.4) > 1.3 (0.4); Medium: 2.4 (0.9) > 1.8 (0.5)]. Yet, the large panel had statistically the same LI values between the heavy [2.3 (0.9)] and the light [2.2 (0.6)] conditions. Further, LI values were significantly larger for the L1G [Heavy = 2.5 (0.9); Light = 2.1 (0.5)] vs. L1K [Heavy = 1.9 (0.5); Light = 1.3 (0.3)].

Several significant main and interaction effects of Mass, Size, and Task were found on maximum REBA scores (Figure 4). Similar to P_{Risk} results, REBA scores were significantly higher for E1GTop and L1G versus the other tasks. In the case of perceived exertion, RPE_{WB} and RPE_{LB} were significantly affected by Mass and Task, as well as the Size x Task interaction. RPE scores were higher in the heavy vs. light conditions [RPE_{WB} : 2.6 (1.6) > 1.9 (1.2); RPE_{LB} : 2.4 (1.6) > 1.7 (1.3)]. The Size x Task interaction had comparable effects on RPE_{WB} and RPE_{LB} , (e.g., Figure 5).

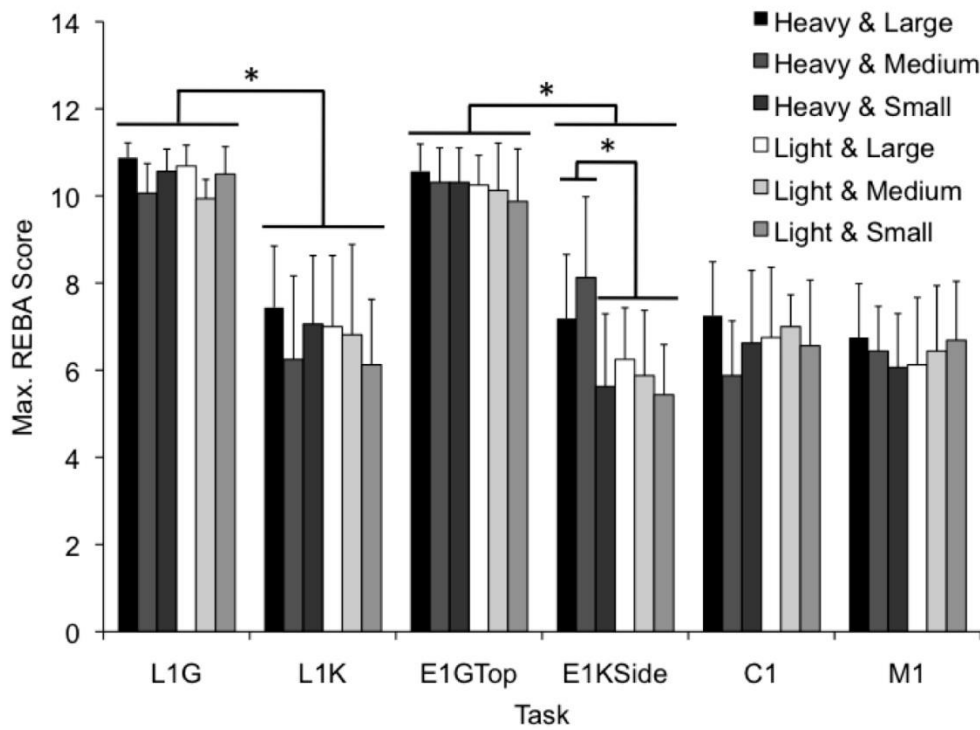


Figure 4. Panel Mass x Size x Task interaction effects on maximum REBA scores. Significant differences between panel sizes within the same task type are indicated by *.

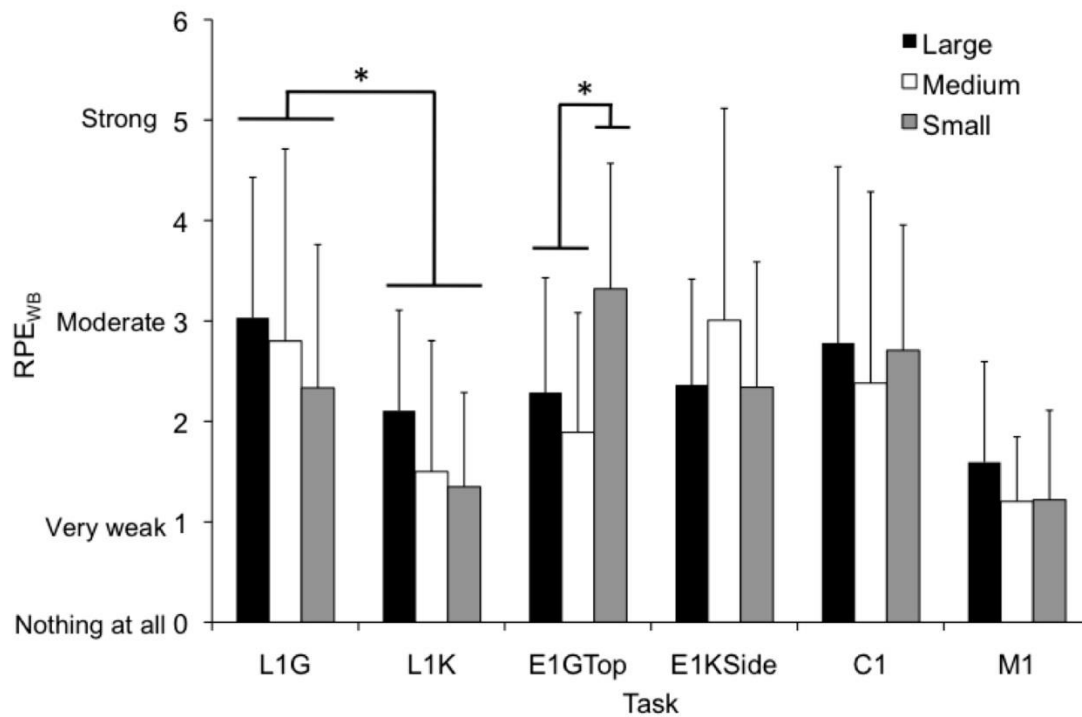


Figure 5. Panel Size x Task interaction effects on whole body RPE scores (RPE_{WB}). Significant differences between panel sizes within the same task type are indicated by *.

3.2. Complementary Assessment of Alternative Tasks By Size

As noted above, the second-step analyses were done separately for small vs. medium and large panels with focus on alternatives within a given task type. For the small panel, there were main significant effects of Mass and Task on all risk assessment measures with two exceptions (Table 3). In general, the heavy condition resulted in higher risk values than the light condition. With respect to Task, L2G yielded risk measures comparable to L1G, yet significantly higher than L1K (by 27 – 164%). The two carrying tasks, C1 and C2, yielded comparable values except for F_x [$C2$ (1175 (564) N) > $C1$ (682 (459) N)] and F_y [$C2$ (3587 (1125) N) > $C1$ (2769 (881) N)].

Table 3. RANOVA results [F value (p)] for effects of Mass (M) and Task (T) on risk measures for the small panel size. Note that Task has five levels (L1G, L1K, L2G, C1, and C2). Results are highlighted in bold if significant.

	Mass	Task	M x T
AP shear force (F_x)	2.51 (0.12)	8.25 (<0.0001)	1.79 (0.13)
Compression force (F_y)	9.39 (0.0026)	20.09 (<0.0001)	1.97 (0.10)
Lat. shear force (F_z)	9.25 (0.0028)	19.99 (<0.0001)	0.54 (0.71)
P_{Risk}	6.50 (0.0019)	338.50 (<0.0001)	1.34 (0.26)
LI	372.38 (<0.0001)	259.16 (<0.0001)	2.69 (0.074)
REBA	1.60 (0.21)	110.71 (<0.0001)	1.54 (0.19)
PE_{LB}	28.83 (<0.0001)	6.05 (0.0004)	0.42 (0.79)
PRE_{WB}	29.74 (<0.0001)	6.50 (0.0003)	0.68 (0.61)

For the medium and large panels, a summary of RANOVA results is presented in Table 4. Significant main effects of Mass, Size, and Task affected all three spinal loads, while F_z was also significantly affected by the Size x Task interaction. In general, the medium and the heavy conditions increased spinal loads by 16 – 53% [F_x : 147 N; F_y : 583 N] and 4 – 11% [F_x : 41 N; F_y : 330 N] respectively, compared to the large and the light conditions. Yet, only E1GTop, E1GSide and E1KSide yielded higher F_z values for the medium vs. large panels. Across the different tasks, comparisons of F_x values indicated E1GSide $\approx$ E1GTop $\approx$ E1KSide > E1KTop, and F_y values indicated E1GTop $\approx$ E1GSide > E1KSide > E1KTop.

Table 4. RANOVA results [*F* value (*p*)] for effects of Mass (M), Size (S), and Task (T) on risk measures for the medium and large panels. Note that Task has four levels (E1GTop, E1GSide, E1KTop, and E1KSide). Results are highlighted in bold if significant.

	Mass	Size	Task	M x S	M x T	S x T	M x S x T
AP shear force (F_x)	6.40 (0.012)	4.66 (0.032)	9.45 (<0.0001)	1.45 (0.23)	0.087 (0.97)	0.89 (0.44)	1.50 (0.22)
Compression force (F_y)	11.13 (0.001)	15.70 (0.0001)	15.69 (<0.0001)	1.07 (0.30)	0.31 (0.82)	1.03 (0.38)	1.11 (0.34)
Lat. shear force (F_z)	4.63 (0.032)	15.95 (0.0001)	12.90 (<0.0001)	3.33 (0.069)	0.81 (0.49)	3.26 (0.022)	0.22 (0.89)
P_{Risk}	21.72 (<0.0001)	3.79 (0.0529)	331.97 (<0.0001)	0.17 (0.68)	8.19* (<0.0001)	0.86 (0.46)	1.27 (0.29)
REBA	18.67 (<0.0001)	0.58 (0.45)	422.92 (<0.0001)	4.62 (0.0327)	5.05* (0.0021)	0.29 (0.83)	3.17 (0.025)
RPE_{LB}	17.85 (<0.0001)	0.78 (0.38)	4.07 (0.0094)	1.25 (0.27)	0.19 (0.90)	0.51 (0.67)	0.28 (0.84)
RPE_{WB}	35.87 (<0.0001)	0.17 (0.68)	7.87 (0.0001)	0.018 (0.89)	0.58 (0.63)	1.82 (0.15)	0.77 (0.51)

*: Effects of Size are significant for all tasks except E1GSide and E1GTop.

Mass, Task, and their interaction significantly affected P_{Risk} and REBA. E1GTop and E1GSide yielded comparable P_{Risk} and REBA values between the mass conditions, and 98 – 240% and 51 – 105% higher values respectively, compared to E1KSide and E1KTop. Further, P_{Risk} was higher for E1KSide vs. E1KTop in the light condition, yet E1KSide = E1KTop in the heavy condition. Slightly higher REBA scores were found for E1KSide than for E1KTop. RPE_{LB} and RPE_{WB} were significantly affected by Mass (Heavy > Light) and Task (RPE_{LB} : E1GSide $\approx$ E1KSide $\approx$ E1GTop > E1KTop; RPE_{WB} : E1KSide $\approx$ E1GSide > E1GTop > E1KTop).

4. Discussion

In support of a proactive assessment of risks involved with panel erection tasks and alternative design approaches, we hypothesized that panel design factors, specifically panel mass and size, would influence imposed risk levels during common panel erection tasks and that these influences would vary between tasks. Note that in an actual workplace the number of workers involved in a given task varies with these same design factors. Thus, to provide more practically-relevant results the number of workers for each task was adjusted based on field observations. Overall, panel mass, size, and erection task had main and interaction effects on the set of risk measures, though to varying degrees (e.g., Table 2). The effects of panel mass were quite straightforward and consistent with initial expectations, in that spinal loads, LI values, and RPE scores increased in the heavy vs. light condition. For most of the tasks, however, risk levels were comparable between the three fairly divergent panel sizes.

The effects of panel mass are consistent with earlier findings, specifically that handling heavy objects and/or heavy tasks are injury risk factors among residential carpenters and laborers (Lipscomb, Dement, Li et al., 2003; Spielholz et al., 2006). In this study, the respective mass differences between the light and heavy conditions were 23 kg (77%), 43 kg (97%), and 54 kg (100%) for the small, medium, and large panels respectively. The heavy condition caused increases of 12 ~ 18% in peak spinal loads, 19 ~ 46% in LI values, and ~36% in RPE scores, and thus represent effect sizes of apparent practical relevance. However, P_{Risk} values and REBA scores for a given task were essentially insensitive to the mass condition (Figure 3 and 4). Both the lumbar risk model and REBA primarily consider body kinematics, suggesting that body movements do not differ enough between the mass conditions to yield different P_{Risk} values and REBA scores. Preliminary analyses of trunk kinematics support this, since differences in panel mass within a given task yielded only 0.1 – 6° differences in maximum trunk angles (Kim et al., 2009). For a given task, the effect of panel size was either small or inconsistent (Figures 3, 4 and 5), depending on the specific assessment tool. Note that this study did not aim to assess the “true” effects of size, but rather to assess risk levels during panel erection tasks with levels of panel design factors commonly used in practice.

Initial vertical panel placement affected risk levels. These levels were higher for a given task if the panel was placed initially on the ground vs. knuckle height, which agrees with existing studies (Faber et al., 2009; Ferguson et al., 2002; Lavender et al., 2003). Tasks originating from ground level (E1GSide, E1GTop, L1G and L2G) resulted in $P_{\text{Risk}} > 88\%$ and REBA scores > 10 (high risk level), whereas tasks starting at knuckle height (E1KSide, E1KTop and L1K) had $P_{\text{Risk}} < 45\%$ and REBA scores < 7 (medium risk level). This effect of initial height was less pronounced on spinal loads, the revised NIOSH equation, and RPE, which is potentially attributable to a differential focus of each tool on risk.

Considering the magnitude of the effects of mass and size, the results suggest that panel mass is an important design factor, and one that could have a substantial impact on WMSD risk levels among workers performing common panel erection tasks. In this study, using unsheathed (light) panels, which decreased panel mass by 23 – 54 kg, yielded ~ 12 – 46% decreases in risk assessment measures across a range of panel erection tasks. A review of intervention studies suggests that $\geq 14\%$ reduction in mechanical exposure likely leads to a concomitant improvement in musculoskeletal health (Lötters & Burdorf, 2002). Hence, panel designers could be encouraged to take the total mass of a panel into consideration, such as when deciding upon panel component materials and how to “break up” or panelize the walls for a given floor plan. In addition, there may be value in minimizing the total number of sheathed panels, with sheathing instead installed, at least partially, on site rather than in the factory. However, simply reducing panel mass by these approaches does not guarantee a reduction in overall exposures, since the overall panel erection process would change and could result in increased overall exposures. More importantly, any change in the overall panel erection process could compromise on-site productivity. These concerns regarding overall exposures and productivity emphasize the necessity for a system that can collectively consider physical demands and productivity and allow panel designers to assess the compromises involved.

Eventual use of our DSS will allow panel design factors to be considered not only to determine panel specifications, but also to address the panel stacking order and build sequence problems. The current results suggest potential “rules” to be used by the system, as well as more general practical guidance for panel manufacturers and builder, some of which are also applicable to the traditional wall building process. For example, heavy panels could be stacked close to knuckle height in a stack to raise the initial panel height. However, the design and construction plans should allow for the minimization or elimination of multiple handling, particularly of larger and heavier panels. In other words, workers would be exposed to potentially avoidable exposures and risk if they needed to sort through a stack of panels to get to the next one needed. Further, carrying tasks resulted in relatively high risk levels; panel stacks should thus be located on the worksite to minimize carrying distances. Since spinal loads (F_x and F_y) were higher for C2 than C1, there may be value in encouraging (or training) workers to carry panels in a horizontal orientation. For tasks involving erecting a panel from knuckle height, workers could benefit by alternating between standing at the panel side and top-plate since risk levels were higher for E1KSide than E1KTop. In addition to these recommendations, alternative work processes, such as using assistive devices for panel erection tasks, might be introduced. Care would be needed, though, to ensure that productivity is not compromised. Assistive devices such as pneumatic lifts have exhibited such adverse effects on productivity depending on the characteristics of a panel (Mirka et al., 2003).

A few limitations of this study should be acknowledged. First, the participants had no formal experience in panel erection tasks, though some participants had experienced general carpentry. All participants observed video recordings of panel erection tasks during the preliminary session, and had opportunities to practice each task during data collection sessions. Physical competency and perceptions of the participants, however, could differ from those of experienced carpenters. Indeed, this, and the fact that the tasks were not simulated over the typical duration of a working day, may explain the relatively low reported levels of perceived exertion (RPE). We also assume that the risks reported here are conservative, and that any designs or approaches that reduce them will also benefit actual workers. Second, due to constraints in the laboratory equipment, participants’ movements were somewhat restrained, and they were asked to keep their hands on load cells attached to the panels. Though efforts were taken to avoid discomfort and to provide sufficient familiarization, limitations such as these may nonetheless limit external validity. Third, inputs to the multiple logistic regression model (Marras et al., 1993) were obtained here using a set of passive markers, while the model was developed using different technology (i.e., lumbar motion monitor, LMM). However, presuming rigid body motion of the thorax, the current use of individual markers and marker cluster was expected to provide information comparable to an LMM, in particular related to angular velocities (to which the risk estimation model is more sensitive versus orientations). The difference in technology, though, still may have biased estimated P_{Risk} values. Fourth, we did not consider suboptimal working conditions, such as a reduced crew size, or unstable, uneven, or slippery surfaces. Fifth, quantitative descriptions of risks were not determined in other (more extreme) situations, such as when handling smaller or larger panels; only the most common situations were assessed.

The present work estimated WMSD risks resulting from common panel erection tasks under conditions of different panel masses and sizes. It should be noted that the set of risk measures suggests that many of common panel erection tasks impose a high risk on workers while handling panels, independent of or dependent upon panel mass and size. Though there are some inconsistencies in predicted risk levels among the risk assessment tools, there was consistent evidence that a reduction in panel mass can lead to a decrease in spinal loads, LI values, and perceived exertion, and that manipulating panels from the ground results in higher risk levels. Some practical guidance was suggested based on the results. In addition, given the existence of centralized designers in off-site panel production, the current information on risk levels can be exploited by a system like the DSS to proactively control WMSD risks during the entire panel erection process. To enhance the likelihood that such an approach is used, it will be necessary to ensure that rules or recommendations improve (or at least do not compromise) on-site productivity.

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3.3. Assessing the benefits of an additional worker during panelized construction tasks

Kim S, Nussbaum MA, Jia B: [2012] The benefits of an additional worker are task-dependent: assessing low-back injury risks during prefabricated (panelized) wall construction. *Applied Ergonomics* 43:843-849.

Abstract

Team manual material handling is a common practice in residential construction where prefabricated building components (e.g., wall panels) are increasingly used. As part of a larger effort to enable proactive control of ergonomic exposures among workers handling panels, this study explored the effects of additional workers on injury risks during team-based panel erection tasks, specifically by quantifying how injury risks are affected by increasing the number of workers (by one, above the nominal or most common number). Twenty-four participants completed panel erection tasks with and without an additional worker under different panel mass and size conditions. Four risk assessment methods were employed that emphasized the low back. Though including an additional worker generally reduced injury risk across several panel masses and sizes, the magnitude of these benefits varied depending on the specific task and exhibited somewhat high variability within a given task. These results suggest that a simple, generalizable recommendation regarding team-based panel erection tasks is not warranted. Rather, a more systems-level approach accounting for both injury risk and productivity (a strength of panelized wall systems) should be undertaken.

1. Introduction

Prefabrication technologies are being adopted increasingly by residential production builders in the UK ([The Housing Forum, 2004](#)), US ([Wakefield, et al., 2001](#)), and other countries. Prefabricated building components (e.g., panelized walls) are typically produced off-site in a factory and arrive at the construction site more completely assembled than relatively raw components employed in traditional construction. The former can be substantially larger and heavier than the latter; common widths of panelized walls (panels) range from 1.2 to 6 m, and these can have masses up to ~ 250 kg ([Nussbaum, et al., 2009](#)). Not surprisingly, multiple workers, as a team, typically perform panel erection tasks (e.g., lifting, carrying, erecting, etc.). In the context of designing and/or evaluating such tasks, a critical issue to be addressed is the influence of multiple workers in terms of ergonomic exposures and injury risks, which prior work has demonstrated to be considerable (Kim, et al., 2011).

Team manual materials handling (MMH) is a strategy adopted in many industries (e.g., health care, construction) when an object is heavy, large, and/or awkward to handle, and when mechanical aids are unavailable or infeasible to use ([Johnson & Lewis, 1989](#); [Sharp, et al., 1993](#)). The use of team MMH generally assumes that the total load and effort are shared, evenly or otherwise, among team members during MMH tasks and that injury risks thereby decrease. Although an increase in the number of team members clearly yields a increased lifting capacity, evidence on the lifting capacity of an individual team member is conflicting, with such capacity found to be unaffected ([Sharp, et al., 1997](#)), decreased ([Karwowski & Mital, 1986](#); [Lee, 2004](#)) or increased ([Lee, 2004](#); [Mital & Motorwala, 1995](#)) with teams composed of > 2

members. Furthermore, during asymmetric lifting (i.e., loads are to the right or left of the body mid-line), two-person team lifting can result in higher lateral shear forces on the lumbar spine than individual lifting ([Marras, et al., 1999](#)). A comprehensive review on team lifting ([Barrett & Dennis, 2005](#)) noted that physical demands are affected by many factors, including the characteristics of team members, the number of team members, the specific tasks, and the environment. Therefore, a generalized recommendation on the use of team MMH seems unavailable at present, and it appears difficult to predict *a priori* either the qualitative or quantitative benefits of team MMH in diverse contexts.

With the off-site production of panels in residential construction noted above, early design decisions can potentially carry broad “downstream” impacts on ergonomic risk and productivity during panel erection processes, corresponding to the contemporary emphasis on a prevention-through-design (PtD) philosophy (e.g., [Behm, 2005](#); [Gambatese, et al., 2005](#); [Gambatese & Hinze, 1999](#)). To facilitate effective decision-making by panel designers (to minimize ergonomic risks), we are developing a decision support system (DSS) that will enable early assessments of both ergonomic and productivity concerns with panel design choices ([Nussbaum, et al., 2009](#)). Outputs of the DSS will include detailed ergonomic risks and worker utilization, and which will be obtained by simulating the entire panel erection process ([Nussbaum, et al., 2009](#); [Shewchuk, et al., 2009](#)). Yet, such simulation requires information regarding alternative worker assignments in panel erection tasks with regard to ergonomic risks. More specifically, implementing the DSS requires knowing whether/how adding an additional worker to a team of workers will affect ergonomic exposures and risks while performing panel erection tasks. Such information is currently lacking, however, either in general ([Barrett & Dennis, 2005](#)) or specific to panel erection tasks.

In support of both these general and specific needs, the current study aimed to assess how an additional worker affects the level of ergonomic risk incurred during several common panel erection tasks with different panel masses and sizes. Low back injury risk was of primary interest, since low back disorders are common musculoskeletal outcomes in residential construction (e.g., [Fredericks, et al., 2005](#); [Lipscomb, et al., 2009](#)). While diverse factors can affect physical demands during team MMH, and team MMH may cause adverse effects (e.g., increased spinal shear forces), Dennis & Barrett (2003) suggested that members of two-person lifting teams tend to adopt a strategy to prevent either member from bearing an excessive load. As such, we hypothesized that the use of an additional worker during panel erection tasks would either reduce or have no effects on the level of ergonomic risks, though these effects would vary depending on the specific task conditions.

2. Material and methods

The current study builds on previous work ([Kim, et al., 2011](#)), and uses very similar methods. As such, a summary of the methods employed is provided here, and the reader is referred to the noted publication for additional details. A convenience sample of 24 participants (19 males and 5 females) completed the experiment. Mean (SD) age, stature, and body mass were 24.2 (4.8) yrs, 174.2 (8) cm, and 71.4 (12.8) kg, respectively. Inclusion criteria were that participants

be physically active and have no illnesses, injuries, or musculoskeletal disorders within the past year that limited their daily activities. Participation involved one preliminary (familiarization) and two experimental sessions, with the latter completed at least two days apart. All participants gave informed consent prior to any data collection, following procedures approved by the Virginia Tech Institutional Review Board.

2.1 Experimental Design and Procedures

Participants completed simulated panel erections tasks under several conditions that involved varying panel size, mass, the specific task, and presence of an additional worker. These conditions were determined as common and representative, based on a total of 1443 panel handlings observed at 10 different home building sites (Nussbaum, *et al.*, 2009). From this, frequencies were obtained for diverse MMH tasks, techniques, panel types, and sizes. A questionnaire was also administered to 18 construction workers to determine which tasks were considered to involved the highest physical demands and injury risk. Results from both were used to determine a subset of common panel configurations and MMH tasks involved in panelized construction that are also relatively physically demanding; this subset was used in the current experiment.

In this study, *Panel Size* (width) had three levels [small (1.2 m x 2.4 m), medium (1.2 m x 2.4 m) and large (3 m x 2.4 m)]. *Panel Mass* had two levels [unsheathed (light) vs. sheathed (heavy)]. *Task* type had eight levels, including lifting, erecting, carrying, and moving. Based on frequency of use as noted above, slightly different types were considered for the small panel, and for medium and large panels. As such, for the small panel, Task types included: a) Lifting panel horizontally that is initially placed either on the floor (L1G) or at knuckle height (L1K); b) Carrying a panel held in a horizontal orientation (C1); and c) Pushing a vertically-oriented panel forward along the bottom edge (M1). Note that only four levels were described here, since the use of an additional worker was not included for other levels due to impracticality and other levels were not examined in the interest of experimental efficiency. For the medium and the large panels, Task types included: a) L1G, L1K, C1, and M1; b) Erecting a panel so that it stands vertically while a participant stands either at panel top-plate with panel initially placed on the floor (E1GTop), or at panel side with panel initially held at the knuckle height (E1KSide); and c) Erecting a panel so that it stands vertically while a participant stands either at panel top-plate with panel initially held at the knuckle height (E1KTop), or at panel side with panel initially placed on the floor (E1GSide).

Two levels of *Additional worker* were included – No additional worker (nominal number of workers) and Additional worker (nominal number + 1). In the former (i.e., the nominal number of workers), the number of workers varied depending on Mass, Size and Task, and were based on the most common situations observed in practice. The use of one additional worker was based on: 1) observations that one additional worker beyond the nominal level was the most common alternative; and 2) a need to control the size of the experiment. When handling the small panel, one worker was involved for E1GTop and M1 tasks in the light condition, and two workers for the remaining conditions. For the medium panel, one worker was involved for E1GTop and

E1KTop tasks in the light condition, and two for the remaining task conditions. To accommodate the relatively low capacity of four female participants (as determined in the preliminary session), three workers were used as the nominal number in the heavy condition. For the large panel, two workers were used in the light condition and three in the heavy condition. The relative positions of each worker are illustrated for each task in Figure 1. Note that experimenters (including the authors) served as team members and as an additional worker in the Additional worker condition. When forming an MMH team for a given task, extreme differences in stature between a participant and experimenters were minimized to the extent possible.

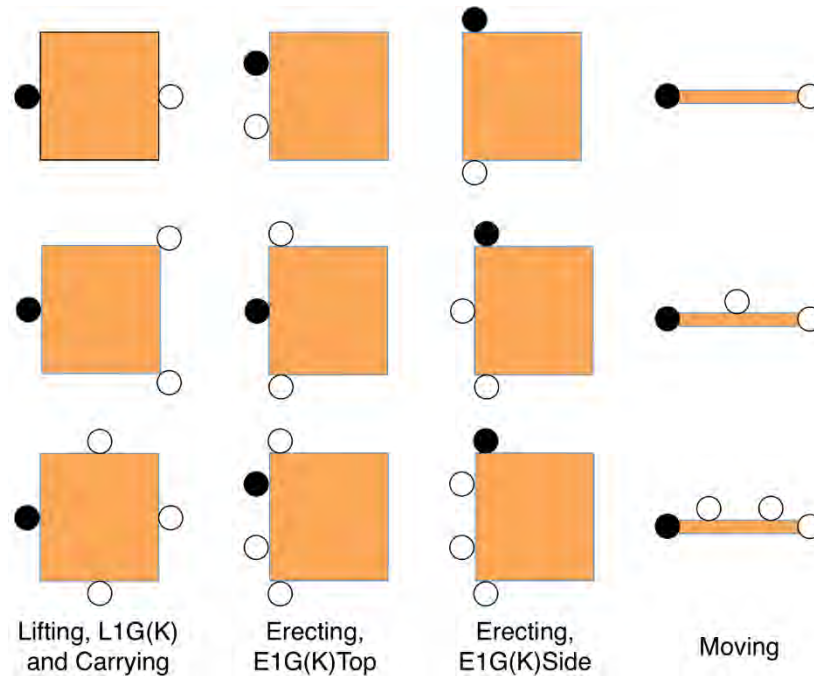


Figure 1. Relative positions of each worker for each panel erection task, using 2, 3, or 4 workers (top to bottom). A filled circle denotes the participant (unfilled circles = experimenters).

Participants completed two experimental sessions (i.e., using two different panel sizes) following a balanced incomplete block design with block size = 2 – each block had the same number of participants. For a particular panel size in each session, participants performed eight different panel erection tasks under all combinations of panel mass and additional worker. In each experimental session, and prior to the panel erection task trials, participants completed initial procedures to calibrate a biomechanical torso model ([see Jia, et al., 2011](#)) that provided estimates of spinal loading. Each session involved a different panel size, with which the participant performed all the combinations of Additional worker, Mass, and Task conditions. Each trial lasted about 10 – 20 seconds and was replicated twice, with ~ 2 min rest between trials, while each session lasted ~ 3 hours.

2.2 Instrumentation

External kinetics (triaxial forces and moments) were obtained using two force platforms (AMTI OR6-7-1000, Watertown, MA), and two triaxial load cells (AMTI MC3A-6). Load cells were attached on the side of panel and were spaced as a participant preferred for a given task condition after several practice trials. Kinetic data were collected at 1080 Hz, and were low-pass filtered (12 Hz cutoff; 2nd order Butterworth; bidirectional) during off-line data processing. Whole-body postures were captured using a 6-camera marker tracking system (Vicon 524, Vicon system, Los Angeles, CA). Reflective markers were placed over anatomical landmarks ([see Kim, et al., 2011 for detailed marker placements](#)), and clusters of markers were attached over the upper trunk, the lumbosacral joint, and bilaterally on the upper arms, lower arms, lower legs and heels. Selected anatomical markers were referenced to corresponding clusters, and those markers were reconstructed for data collection trials ([Challis, 1994](#)). Motion data were sampled at 120 Hz, and subsequently low-pass filtered with a cut-off frequency of 9 Hz (2nd order Butterworth; bidirectional).

Bilateral muscle activity of three trunk flexors and four extensors were monitored using two telemetered electromyography (EMG) systems (TeleMyo 900, Noraxon, AZ); pairs of disposable bipolar Ag/AgCl electrodes (AccuSensor, Lynn Medical, MI) with a 2.5 cm inter-electrode distance were placed on the skin surface following skin preparation. EMG signals were sampled at 1080 Hz, and then normalized using individual maximum and minimum values obtained through calibration trials (i.e., a set of maximum voluntary contractions and passive trunk flexion). Normalized EMG, along with kinematics and kinetics describe above, were used as input to a three-dimensional dynamic EMG-based model, which was calibrated to each individual, to estimate muscle forces and spinal loads. A more complete description and evaluation of the modeling processes is provided ([Jia, et al., 2011](#)).

2.3 Ergonomic Risk Assessments

A set of four existing methods were incorporated to provide a reasonably broad assessment of musculoskeletal risks (particularly in the low back) associated with a given task condition. These methods included: 1) an EMG-based model of the lumbar spine and associated musculature ([Jia, et al., 2011](#)), to estimate 95th percentile (maximal) spinal compression (F_Y), and anteroposterior and lateral shear forces (F_X and F_Z); 2) a multiple logistic regression model ([Marras, et al., 1993](#)), to estimate the probability of membership in a group at high risk of a low back disorder (P_{Risk}); 3) the revised NIOSH lifting equation ([Waters, et al., 1994](#); [Waters, et al., 1993](#)), to obtain the lifting index (LI) for trials involving lifting (i.e., L1G, L1K and L2G); and 4) ratings of perceived exertion (RPE) for the whole body (RPE_{WB}) and low back (RPE_{LB}) using Borg's CR-10 scale ([Borg, 1990](#)). Further details regarding the application of these methods are available elsewhere ([Kim, et al., 2011](#)).

2.4 Statistical Analyses

Statistical analyses were completed separately for tasks performed with all panel sizes under both Additional worker conditions, and for the subset of tasks performed only with the medium and large panels. More specifically, the first involved repeated-measures analyses of variance

(RANOVAs) on each of the risk assessment measures, with independent variables of Mass, Size (small, medium and large), Task (L1G, L1K, C1 and M1), and Additional worker. In the second analysis, RANOVAs were performed with independent variables of Mass, Size (medium and large), Task (E1GSide, E1KSide, E1GTop and E1KTop), and Additional worker. Maximal spinal loads (F_x , F_y , and F_z) were log-transformed prior to statistical analyses to achieve normally distributed residuals. Significant effects were followed by post-hoc pairwise comparisons (Tukey's HSD or Student's t tests). All statistical analyses were performed with JMP 9.0 (SAS Institutes, Inc., Cary, NC), and a p -value of < 0.05 was considered to be statistically significant. All summary data are presented as means (95% Confidence Intervals); log-transformed values (maximal spinal loads) were back-transformed and are thus presented in the original units. As the effects of Mass, Size, and Task have been reported earlier (Kim et al, 2011), emphasis here was placed on the main and interactive effects of Additional worker.

3. Results

With a few exceptions, use of an additional worker significantly reduced values of the risk assessment measures across levels of Mass, Size, and Task (Table 1). For cases where measures were significantly affected by the use of an additional worker, differences between Additional worker conditions are summarized in Table 2. In the case of tasks performed with all panel sizes (i.e., L1G, L1K, C1 and M1), the presence of an additional worker significantly decreased F_x ($p = 0.0132$) and F_y ($p = 0.0003$), P_{Risk} ($p < 0.0001$), LI ($p < 0.0001$), RPE_{WB} ($p < 0.0001$), and RPE_{LB} ($p < 0.0001$). Further, F_y ($p = 0.0023$) and P_{Risk} ($p < 0.0001$) were significantly affected by Additional worker x Task interactions (Figure 2). LI values were affected by the interaction effects of Additional worker with Mass ($p = 0.007$) and Size ($p = 0.0084$); however, within the same Mass or Size condition, use of an additional worker generally reduced LI values regardless of the specific task (Figure 3).

Table 1. Summary of risk assessment measures [mean (95% CI)] with respect to Additional worker conditions. Larger measures were found in the No additional vs. Additional worker conditions, with significantly larger values highlighted in bold. Note that tasks performed with all panel sizes include L1G, L1K, C1 and M1; tasks performed with only the medium and large panels include E1GSide, E1GTop, E1KSide and E1KTop.

Panel Size	Additional Worker	F _X (N)	F _Y (N)	F _Z (N)	P _{Risk}	LI	RPE _{WB}	RPE _{LB}
All	Without	613 (515, 731)	2534* (2308, 2782)	77 (61, 97)	41.3* (38.3, 43.5)	2.0† (1.8, 2.1)	2.1 (1.7, 2.5)	2.0 (1.5, 2.3)
	With	560 (470, 667)	2370.30 (2159, 2603)	65. (52, 823)	38.4 (35.3, 40.6)	1.5 (1.4, 1.6)	1.6 (1.2, 2.0)	1.6 (1.1, 1.9)
Medium and Large	Without	821 (676, 997)	2919 (2623, 3248)	78 (62, 100)	62.0‡ (56.6, 67.0)	.	2.5 (2.0, 2.9)	2.2 (1.7, 2.7)
	With	705 (580, 856)	2631 (2364, 2928)	66 (52, 84)	56.0 (50.6, 61.0)	.	1.9 (1.5, 2.4)	1.7 (1.2, 2.2)

- * indicates that there are also significant Additional worker x Task interactions.
- † indicates that there are also significant interaction effects of Additional worker with Mass and Size.
- ‡ indicates that there are also significant Additional worker x Size interactions.

Table 2. Summary of the effects of an Additional worker on risk assessment measures for conditions in which this main effect was significant. Values are means (95% CI) of differences (with – without), and a negative sign indicates that a value is reduced with an additional worker.

Task	F _X (N)	F _Y (N)	F _Z (N)	P _{Risk}	LI	RPE _{WB}	RPE _{LB}
L1G	-69 (-116, -21)	-244 (-353, -136)	-9 (-22, 5)	-1.9 (-2.5, -1.2)	-.5 (-.6, -.4)	-.7 (-.9, -.4)	-.7 (-.9, -.5)
L1K	-58 (-94, -21)	-232 (-317, -147)	-10.28 (-17, -4)	-8.2 (-10.1, -6.3)	-.4 (-.4, -.3)	-.5 (-.7, -.3)	-.44 (-.6, -.2)
C1	-117 (-160, -74)	-414.19 (-515, -314)	-50 (-82, -19)	-2.6 (-3.5, -1.7)	.	-.5 (-.7, -.3)	-.2 (-.4, -.03)
M1	-46.47 (-81, -12)	98 (19, 176)	-14 (-44, 16)	1.0 (-.4, 2.3)	.	-.2 (-.3, -.05)	-.2 (-.3, -.02)
E1GSide	-53.76 (-120, 12)	-270 (-422, -118)	-11 (-37, 15)	-4.4 (-5.7, -3.0)	.	-.6 (-.9, -.3)	-.5 (-.8, -.2)
E1GTop	-216 (-285, -148)	-509 (-683, -334)	-6 (-22)	-5.1 (-6.7, -3.6)	.	-.4 (-.7, -.2)	-.3 (-.6, .004)
E1KSide	-152 (-198, -106)	-406 (-518, -295)	-21 (-49, 7)	-7.6 (-6.8, -5.5)	.	-.6 (-.8, -.3)	-.5 (-.7, -.2)
E1KTop	-133 (-183, -84)	-251 (-377, -125)	-2 (-12, 5)	-6.8 (-9.8, -3.8)	.	-.6 (-.9, -.3)	-.6 (-.9, -.3)

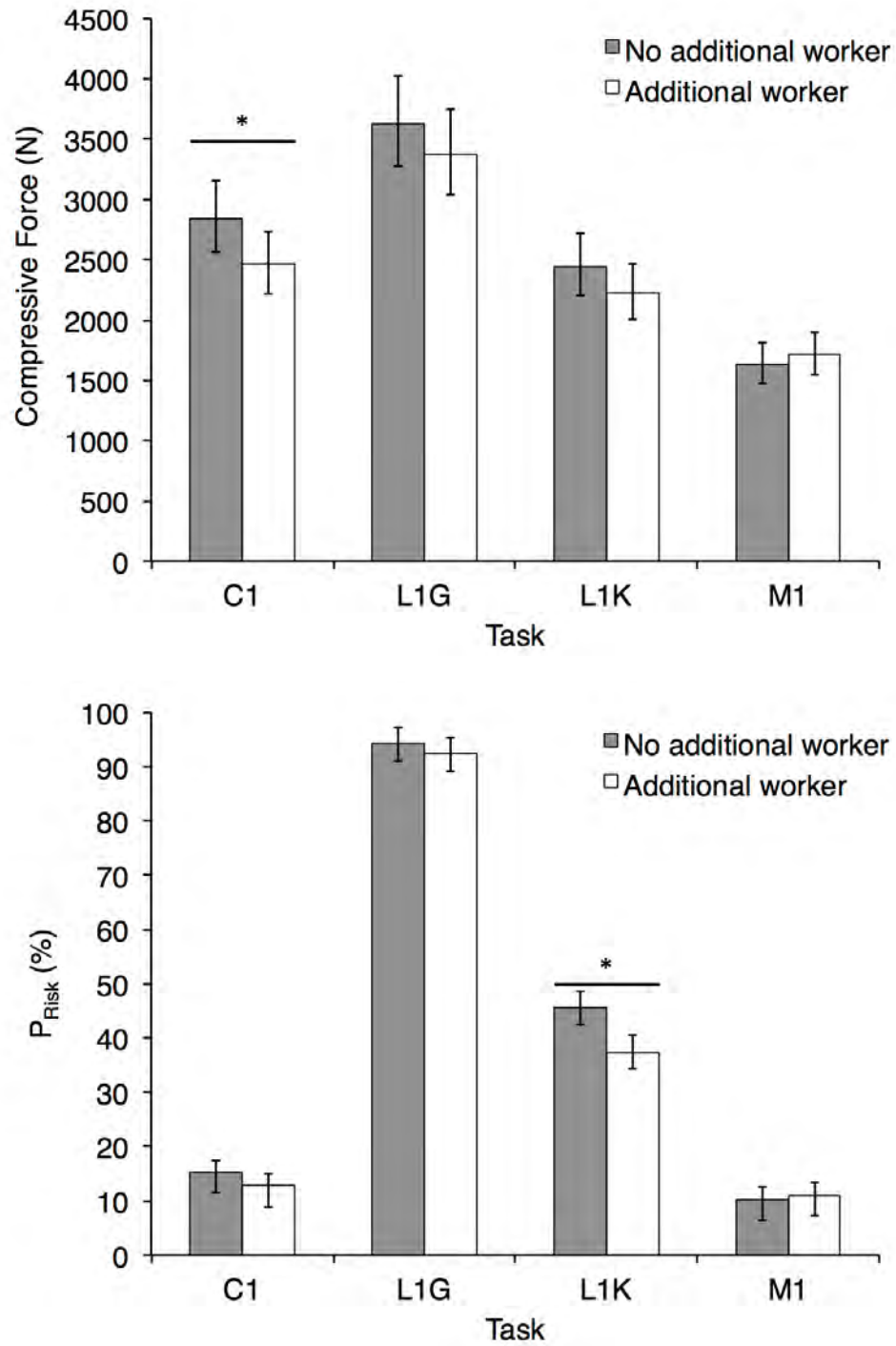


Figure 2. Interaction effects of Task and Additional worker on spinal compressive force (F_z ; Top) and the probability of membership in a group at high risk of a low back disorder (P_{Risk} ; Bottom). Significant reductions from including an additional worker are indicated by *, and error bars indicate 95% confidence intervals.

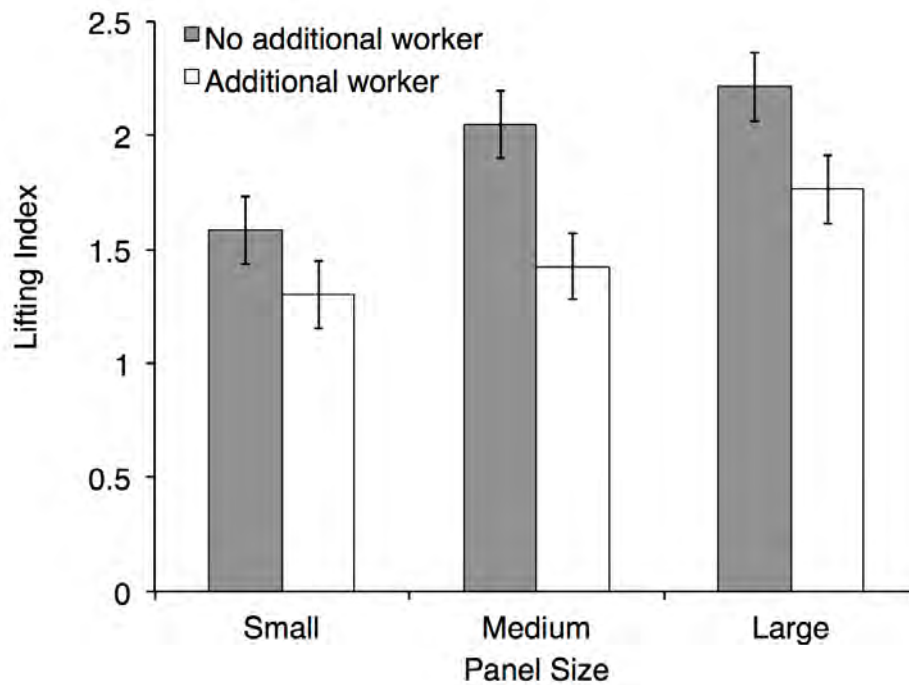
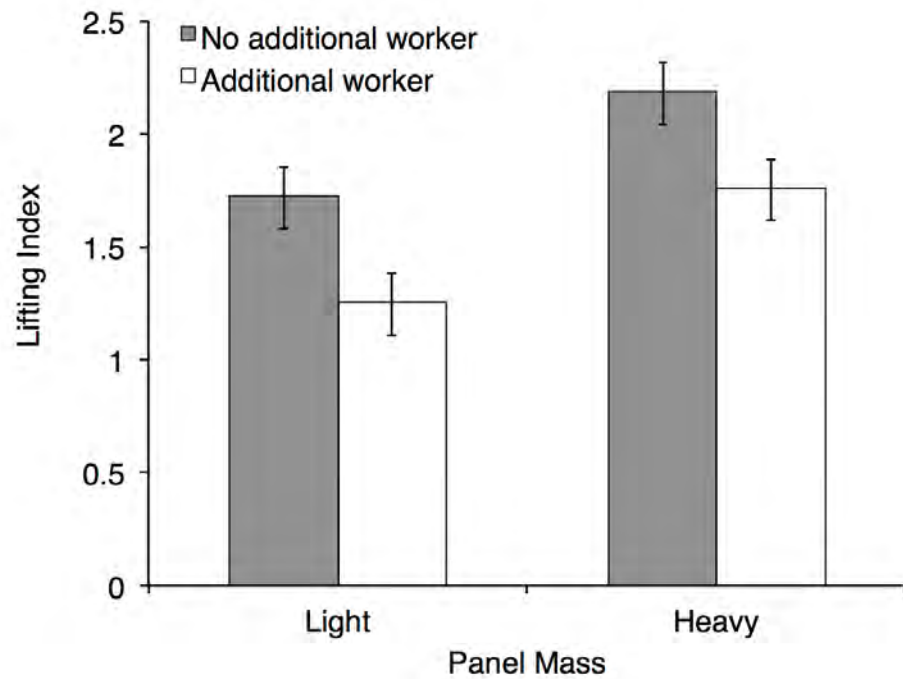


Figure 3. Interactive effects of Mass and Additional worker (Top) and Size and Additional worker (Bottom) on Lifting Index. Within a given mass and size, all decreases with an Additional worker were significant. Error bars indicate 95% confidence intervals.

Regarding tasks performed with only the medium and large panels (i.e., E1GSide, E1KSide, E1GTop and E1KTop), the presence of an additional worker significantly reduced F_x and F_y , P_{Risk} , RPE_{WB} , and RPE_{LB} values (all p values < 0.0001). Additionally, P_{Risk} values were significantly affected by the Additional worker x Size interaction ($p = 0.0403$). Similar to the Additional worker x Size interactions on LI, within the same Size condition the use of an additional worker generally reduced P_{Risk} values (by 18.3% – 27.3%) compared to the No additional worker condition [Medium = 63.2% (32.3%), Large = 60.9% (32.4%)].

4. Discussion

This study examined alternative worker assignments in panel erection tasks with regard to ergonomic risks, and specifically quantified how an additional worker affects ergonomic risks while a team of workers performs panel erection tasks with different panel sizes and masses. Results as a whole indicated that using an additional worker during panel erection tasks is generally beneficial in reducing ergonomic risks, though the magnitude of such benefit varied with the specific task being performed. In contrast, the benefits of an additional worker appeared to be consistent across panel masses and sizes for a given task.

As one may expect, increasing the team size by one additional worker reduced the level of ergonomic risks, though the reduction in some of risk assessment measures was insignificant or minimal (see Tables 1 and 2). Overall, though, the current results are comparable with earlier studies of one- vs. two-person lifting, in that team lifting is associated with lower levels of perceived exertion ([Dennis & Barrett, 2002](#)) and peak spinal compression forces ([Dennis & Barrett, 2002](#); [Marras, et al., 1999](#); [Mital & Motorwala, 1995](#)). Contrary to the present findings, however, those studies reported neither a reduction nor a downward trend in peak spinal shear forces with team lifting. Marras *et al.* ([1999](#)) noted that shear forces decreased when team members were trained to synchronously lift. Given this, one potential reason for the reduced spinal shear forces found here could relate to the procedures employed; participants practiced the tasks and were asked to signal when to start each trial, while the experimenters were instructed to move in a way synchronized to participants. Hence, the current results are perhaps more relevant to an experienced than a novice MMH team, as the former can be expected to have more synchronous behaviors.

While there were ergonomic risk reductions from using an additional worker, the magnitude of this reduction differed between tasks and had rather high variability (Table 2). Spinal loads, P_{Risk} , LI, and perceived exertion (RPE_{WB} and RPE_{LB}) were all reduced on average for all tasks except the moving (M1) task. This is likely linked to the differences in hand force reduction for each task resulting from including an additional worker, given the minimal changes in body kinematics between the Additional worker conditions noted earlier. However, physical demands during team MMH can be affected by relative positions and roles of each team member ([Barrett & Dennis, 2005](#)), as well as by a reduced motivation for individuals in a team ([Karwowski, 1988](#)). These factors could, to a certain extent, account for the task-related differences in ergonomic benefits stemming from including an additional worker. For example, with the moving task, it may be assumed that participants played a lead role during both the Additional

worker conditions because they were positioned to exert forces in the principal moving direction (Figure 1). This assumption is supported by the lack of any considerable changes in maximum hand forces ([Kim, et al., 2009](#)), F_Y and P_{Risk} values between the conditions. Furthermore, variance in body kinematics, kinetics, and muscle coactivity can lead to a large variance in spinal load even during relatively constrained tasks such as repetitive asymmetric lifting ([Granata, et al., 1999](#); [van Dieën, et al., 2001](#)). This, and the complex nature of team MMH (e.g., relative positions and roles of team members, specific tasks, etc.) may explain the large observed variances in the magnitude of ergonomic risk reduction with an additional worker for panel erection tasks that are less constrained and more dynamic.

Considering the general reduction in ergonomic risks, it may be of benefit for residential construction operations to use an additional worker during panel erection tasks (i.e., above the nominal number used otherwise). However, cumulative exposures are also an independent injury risk factor ([Kumar, 1990](#); [Norman, et al., 1998](#)), and any discrete reduction in ergonomic risks using an additional worker could be offset by an increase in the total number of tasks performed by an individual worker over time. In addition, since a crew is a finite resource (i.e., the total number is fixed), using an additional worker for each task can compromise overall on-site productivity, which is a strength of panelized wall systems ([NAHB, 2011](#); [SBCA, 2011](#)). Whether or not to use an additional worker is thus a complex problem subject to worker utilization (including labor costs), cumulative exposure, and on-site productivity, and which is in a class of recognized difficult problems in combinatorial optimization ([Askin & Standridge, 1993](#)).

Given the consistency of additional worker effects across panel masses and sizes, solution approaches to this problem can focus largely on which task would most likely benefit from an additional worker. However, the difficulty in addressing this problem is further compounded by the fact that imposed ergonomic risks vary also with panel size and mass ([Kim, et al., 2011](#)). This emphasizes the need for a system that will allow for a rapid assessment of ergonomic and productivity consequences with alternative panel design choices and their associated construction plans (e.g., different worker assignments). Such a system (i.e., decision support system, DSS) can facilitate a proactive approach to controlling ergonomics risks, and is currently under development (Nussbaum, et al., 2009). The current results will be used in the DSS as part of a simulation package to assess the multi-criteria consequences of alternative designs, task scheduling, and worker assignments. Specifically, the current results contribute to a database of exposures and risks, which thereby allow for estimates of both ergonomic and productivity consequences (Nussbaum, et al., 2009). Subsequently, numerous simulations can be run, each using different rules, assumptions, or procedures, to assess the effects of these on selected criteria. As examples with relevance to the current work, a builder could determine the relative merits (e.g., in terms of low back injury risk, build time, and/or labor costs) of hiring an additional worker to complete a particular structure or using an additional worker for certain panel erection tasks.

This study has a few potential limitations. First, the participants had no experience with panel erection processes, so that their physical perceptions and performance could differ from those

of experienced construction workers. Manual lifting strategies adopted by novices vs. experienced workers can be different and potentially less safe (Authier, *et al.*, 1996; Chen, *et al.*, 2011). However, there is conflicting evidence regarding whether experienced workers have higher or lower torso kinematics and kinetics (Granata *et al.* 1999, Marras *et al.* 2006, Plamondon *et al.* 2010). In this study, each task had specified initial and final wall panel locations as well as predefined positions of co-workers. Feasible alternate work strategies were thus rather limited so that a relatively small difference is expected in terms of work strategies adopted by novices vs. experienced workers. Furthermore, participants practiced each task to their satisfaction during data collection sessions, and any designs or approaches that reduce the risks imposed on novices can be expected to also benefit experienced workers. Second, body movements of participants were likely restrained to some extent due to constraints in the laboratory equipment (e.g., the participants were asked to keep their hands on load cell attached to the panels). Thus, external validity may be limited regardless of our efforts to provide sufficient familiarization. Third, the EMG-based model of lumbar spine was participant-specific (scaled to individual anthropometry), yet not gender-specific (the same scaling methods were used for both males and females). As such, there may be systematic errors in spine loads predicted for one or the other genders, yet the use of a within-subjects design likely limited substantial confounding of the major results found here with respect to the use of an additional worker.

Fourth, the effects of the use of an additional worker may have been influenced by potential confounding factors such as the height and strength difference in MMH team members, team coordination, etc. However, it can be expected that workers in practice are unlikely to be able to consider such factors while performing panel erection tasks, which thus supports the practical relevance of our study. Fifth, this study did not consider suboptimal working conditions (e.g., an insufficient crew size, or unstable, uneven, or slippery surfaces). Ergonomic risks likely increase when the nominal number of workers performs panel erection tasks in suboptimal vs. optimal conditions. For example, Shin and Mirka (2004) indicated that the peak L5/S1 moment increases with lifting on an inclined vs. flat surface. It can thus be speculated that the magnitude of ergonomic benefits obtained from using an additional worker would be higher under more realistic conditions (i.e., outside the lab), especially given that use of an additional worker could enhance load stability.

In summary, a systematic reduction in the level of ergonomic risks was observed overall with the use of an additional worker, though the magnitude of this reduction was different between tasks. These results may lead to a simple generalizable recommendation of encouraging the use of an additional worker while performing panel erection or similar MMH tasks whenever suitable. However, caution should be also taken in using an additional worker, because the ergonomic benefits from using an additional worker are task-dependent and affected by many factors, and could be negated when cumulative exposures are considered. Furthermore, the use of an additional worker with a fixed crew size could decrease on-site productivity. There is thus a continuing need for a high-fidelity study that focuses on the complex nature and outcomes of team MMH, and a more systems-oriented approach that addresses both ergonomic risks and productivity. Future work is also needed to determine whether the current

results regarding the effects of an additional worker, obtained in a controlled laboratory setting, are also found in actual work environments.

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3.4. Estimating ergonomics risks during a range of panelized construction tasks

Kim S, Nussbaum MA: Interpolating/extrapolating ergonomic risks from discrete samples: a case study on panelized wall handling. In preparation.

Abstract

Residential construction workers are at a high risk of work-related musculoskeletal disorders (WMSDs). A system-level simulation approach was proposed earlier, to proactively control WMSDs in this industry, and with a focus on prefabricated (panelized) wall systems. Integration of ergonomic considerations in the simulation approach requires prediction tools for ergonomic exposures and risks for various, often team-oriented panel installation tasks. Such tasks, however, are beyond the focus of the existing prediction tools. Generalized linear regression models were developed to predict select ergonomic risk measures for common panel installation tasks (i.e., lifting, different types of erecting, carrying, and moving), using task-based parameters as predictors. The specific predictors were panel size, mass, origin height, and the number of workers. The model development results suggest that a few risk measures can be adequately modeled (e.g., $r^2 > 0.7$) for lifting and erecting tasks, using only the task-based parameters. Further, a rigorous model validation, using a dataset independent of model development, supported predictive validity only for the lifting index (LI: $r^2 = 0.71$). LI prediction errors, however, appeared considerable, so a change in predicted LI values may have more practical value. Note that analysis and validation of the models for risk measures is still in process. A need for predictors that can reflect variation in work strategy and individual differences is discussed.

1. Introduction

Residential construction work involves a variety of manual (and typically physically demanding) tasks in a changing work environment. Such aspects of construction work can place construction workers at a high risk of work-related musculoskeletal disorders (WMSDs). In fact, construction workers in general, and carpenters in particular, experience relatively high incidence rates of injury and illness compared to all industries, and overexertion and repetitive motion accounted for ~30% nonfatal lost workday cases (Bureau of Labor Statistics, 2014). Preventing WMSDs in construction, however, is considered to be challenging compared with other industries due to, for example, substantial task variability and irregular work periods (Forde & Buchholz, 2004).

Prefabricated (panelized) wall systems are one example of current housing technologies to improve productivity and efficiency, by shifting wall assembly processes from individual construction sites to a controlled factory environment. Fully assembled panels – which can be >4.8 m wide and weighing >113 kg – are shipped to a construction site, and handling them (e.g., unloading, transferring, installing) is a primary task of on-site workers. This centralized production of panels has been recognized as an opportunity to effectively control WMSDs, by integrating ergonomic considerations for on-site workers during the panelized wall design

process (see Nussbaum, Shewchuk, Seol, & Guo, 2009 for details on panelization and approaches). Further, and to facilitate such integration, these authors presented the development of a computerized decision support system (DSS) for panelized wall systems. In this, a discrete event simulation approach was implemented to permit a system-level simulation of the entire process from panel design through panel stacking to on-site construction, while considering complex interactions between workers and panelization alternatives (e.g., panel sizes, stacking orders, crew size, etc.) (Shewchuk et al., 2015).

Consideration of ergonomics issues in simulation modeling requires quantification tools (i.e., prediction tools) for ergonomic exposures/risks at the worker level for a given panelization alternative. Each alternative will cause changes in work parameters for panel installation tasks, such as individual panel sizes, masses, origin heights, locations, and available number for workers for a given panel installation task. Earlier work assessed ergonomic risks in lab-based task recreations for several common panel installation tasks and with specific work parameters (Kim et al., 2011; 2012). However, it is infeasible to experimentally obtain ergonomic risks for all possible panelization alternatives. Using a prediction tool therefore has clear efficiency and practical benefits. A few quantitative tools exist, such as the 3D Static Strength Prediction Program™ (University of Michigan Center for Ergonomics, 2001) and different types of regression models (Arjmand et al., 2011; Fathallah et al., 1999; McGill et al., 1996; Parkinson & Callaghan, 2009). These, however, focus on lifting performed by a single worker under limited circumstance, and often require detailed body kinematics and/or external kinetics as input variables. Panel installation tasks, though, are diverse and frequently require multiple workers. In simulation modeling, there is no actual worker to obtain detailed body kinematics and external kinetics.

The objective of this study was thus to develop and evaluate models to predict ergonomic risks for common panel installation tasks, using task-based parameters as predictors. Our specific emphasis for predictors was panel size, mass, the origin height, and the number of workers, as these are important aspects that with influence physical demands and ergonomic risks. This study is a continuation of our previous efforts (Kim et al., 2011; 2012), in that the earlier data were used to develop task-specific regression models to predict ergonomic risk measures. A separate lab-based study was completed to assess predictive validity of the model, and the study was designed to vary the predictors both within and outside the ranges considered in the model development data. This is particularly important, to understand the prediction performance of the models developed, and which is generally lacking in existing studies.

2. Methods

2.1 Participants

Experimental data from previous work (Kim et al., 2011) were used to develop the prediction models for ergonomic risk measures. A brief summary of this experiment is provided here, as relevant to the current study, and more details can be found in the noted publication. In the study, a total of 24 participants participated, whose mean (SD) age, stature, and body mass

were 24.2 (4.8) yrs, 174.2 (8) cm, and 71.4 (12.8) kg, respectively. For assessment of prediction models, a separate set of 10 male participants completed both one preliminary (familiarization) and one experimental session. This latter sample had mean (SD) age, stature, and body mass of 21.6 (1.0) yrs, 173.7 (6.4) cm, and 72.1 (8.6) kg, respectively. Participants were physically active and had no self-reported illnesses, injuries, or musculoskeletal disorders within the past year that limited their daily activities. All participants gave informed consent prior to any data collection, following procedures approved by the Virginia Tech Institutional Review Board.

2.2 Experimental Design and Procedures

Study for prediction model development (Study 1): Participants simulated panel installation tasks under several conditions, involving different panel sizes, masses, task types, and the presence of an additional worker. Panel *Size* (width) had three levels (small, medium, and large), and panel *Mass* had two levels (unsheathed vs. sheathed); specific values of each condition are presented in Table 1.

Table 1. Panel masses and dimensions.

	Small Panel (1.2 m × 2.4 m)	Medium Panel (2.4 m × 2.4 m)	Large Panel (3.0 m × 2.4 m)
Unsheathed (kg)	30	44	54
Sheathed (kg)	53	87	108

Panel installation *Task* types had eight levels for the medium and large panels, including lifting, erecting, carrying, and moving. A slightly different set of tasks was considered for the small vs. the medium and large panels, as some combinations of tasks and panel sizes appear not practical and were not often observed in the workplace. For the small panel, *Task* types included:

- Lifting a panel horizontally that is initially placed either on the floor (L1G) or at knuckle height (L1K)
- Lifting a panel off the floor, such that it is oriented at ~45 degrees to the ground at lift completion (L2G)
- Carrying a panel held either in a horizontal orientation (C1) or at a ~45 degree orientation to the ground (C2)
- Erecting a panel so that it stands vertically while the participant stands either at: a) panel top-plate, with panel initially placed on the floor (E1GTop); or b) panel side, initially held at the knuckle height (E1KSide)
- Moving a vertically oriented panel forward along the bottom edge (M1).

For the medium and large panels, *Task* types included:

- L1G, L1K, C1, E1KSide, E1GTop, and M1
- Erecting a panel so that it stands vertically while a participant stands either at a) panel top-plate, with panel initially held at the knuckle height (E1KTop), or b) at panel side, with panel initially placed on the floor (E1GSide)

The presence of an *additional worker* had two levels, specifically No additional worker (nominal number of workers) and Additional worker (nominal number + 1). The nominal number of workers varied depending on Mass, Size, and Task, and was based on the most common situations observed in practice. Of note, experimenters served as manual material handling team members for a given task, as well as an additional worker in the Additional worker condition.

Participants performed all the combinations of Mass, Task, and Additional worker conditions for two panel sizes, following a balanced incomplete block design. Prior to the panel installation task trials, participants completed a calibration procedure for the electromyography-based torso

model for estimating biomechanical spinal loading (see Jia, Kim, & Nussbaum, 2011). For a given panel, each trial was replicated twice, with ~2 of min rest between trials, and completing all the experimental conditions lasted ~3 hours.

Study for model performance validation (Study 2): Participants completed a set of selected task types under some of the same conditions and some different conditions from the earlier study. The conditions were selected to permit assessing model performance both within and outside the range of task parameters (e.g., panel mass/size, panel origin height) considered in Study 1; as such the model was assessed in terms of the ability to interpolate and extrapolate from conditions used to specify the prediction models. More specifically, the select task types included:

- L1G, E1GSide, E1GTop, and M1
- Lifting a panel horizontally that is initially placed either at knee or knuckle height, using a custom adjustable-height platform
- Erecting a panel so that it stands vertically while a participant stands at the panel side, and with the panel initially placed at either at knee or elbow height

The panels employed included: one new panel size (1.8 m × 2.4 m) with two mass conditions [unsheathed (30 kg) vs. unsheathed (63 kg)], and three existing panels (i.e., sheathed small, medium, and large panels).

For a given panel, participants performed four task types such as one type of lifting and erecting, E1Gtop and M1. Each trial was replicated twice, with ~2 min of rest between trials, and completing all the experimental conditions lasted ~2 hours. The presentation order of panels and task types was randomized. The nominal number of workers was generally considered to control the size of the experiment, yet additional worker(s) were used based on participants' confidence and strength. Similar to the earlier study, participants first completed a calibration for the EMG-based torso model before panel installation tasks.

2.3 Instrumentation

External kinetics (triaxial forces and moments) were obtained using two force platforms (AMTI OR6-7-1000, Watertown, MA) and two triaxial load cells (AMTI MC3A-6). Load cells were attached on the side of a panel and were spaced as a participant preferred for a given task condition after several practice trials. Kinetic data were collected at 1080 Hz and were low-pass filtered (12 Hz cutoff; 2nd order Butterworth; bidirectional) during off-line data processing. Reflective markers and clusters of markers were used to monitor whole-body kinematics, using a 6-camera motion capture system (Vicon 524, Vicon system, LA) for Study 1, and an 8-camera system (Vicon MX) for Study 2. Note that details regarding marker and cluster placements and processing have been reported elsewhere (Kim et al., 2011). Motion data were sampled at 120

Hz, and subsequently low-pass filtered with a cut-off frequency of 9 Hz (2nd order Butterworth; bidirectional).

Bilateral muscle activity of three trunk flexors and four extensors were sampled at 1080 Hz, using two telemetered EMG systems (TeleMyo 900, Noraxon, AZ) for Study 1 and one telemetered EMG system (TeleMyo DTS) for Study 2. Pairs of disposable bipolar Ag/AgCl electrodes with a 2.5 cm inter-electrode distance were placed on the skin surface following skin preparation. A more complete description and evaluation of the EMG modeling processes is provided elsewhere (Jia et al., 2011).

2.4 Risk Assessment Measures

From each study, several measures were obtained to quantify the relative risk posed during the tested panel installation tasks. Specifically, low back disorder risk was assessed using the NIOSH Lifting equation (Waters et al., 1994); the multiple logistic regression model of Marras et al. (1993); and maximal 3-D external moments and reaction forces at the lumbosacral joint (Jia et al., 2011). Whole-body postures were assessed using the Rapid Entire Body Assessment (REBA) tool (Hignett & McAtamney, 2000).

2.5 Prediction Model Development and Selection

To predict risk measures, separate regression models were developed for each task type (i.e., L1, E1Top, E1Side, C1, and M1) and each risk measure, using task-based parameters as predictors. The predictors considered were panel mass, size, origin height, and the number of workers, and each generalized linear regression model had the following form:

$$Y = b_0 + b_1M + b_2S + b_3H_O + b_4NW + \text{interaction terms}$$

where Y is the risk measure; b_0 - b_4 are regression coefficients; and M , S , H_O , and NW are the panel mass (kg), size (m), origin height (m), and the number of workers, respectively. The reciprocal and 2nd order polynomial terms of predictors were also explored in the model. The binomial family was assumed for P_{RISK} since the range of P_{RISK} value was 0 and 1. Other risk measures were positive, so both the normal and gamma family with an identity link function were considered. Note that H_O was excluded from the carrying and moving tasks, as not pertinent to those tasks.

Prediction model development and selection were completed using the R statistical software (R Core Team, 2014). For each risk measure and task type, several candidate models were first constructed based on our previous findings on the effects of panel design parameters (Kim et al., 2011) and the availability of an additional worker (Kim et al., 2012) on risk measures, and using the glmulti R package (Calcagno, 2013). The latter allows exploring all possible unique generalized linear models with the predictors provided, while considering up to 1st order interactions. Candidate model selection was guided by the Akaike information criterion (AICc) corrected for finite sample sizes. Subsequently, and to select a “best” model, a 10-fold cross validation (CV) was performed 50 times on each of the candidate models (for each risk measure and task type), using the data from Study 1. A best model was selected based on the mean square errors from 50 realizations of 10-fold CV.

2.6 Model Performance Assessment

Performance of the identified (best) prediction models was assessed using two separate data sets (from Studies 1 and 2), and with performance quantified using three common metrics: coefficient of determination (r^2), mean absolute error (MAE), and root mean square error (RMSE) between predicted and true risk measures. It should be reminded that the data set from Study 2 was obtained from the participants not involved in Study 1, and contained conditions both within and outside of the ranges considered in Study 1.

3. Results

3.1 Model performance using Study 1 data

The prediction models performed inconsistently, depending on task types and risk measures (Tables 2-6). Regardless of specific risk measures, relatively better prediction performance was found for the lifting and erecting (E1Side and E1Top) tasks vs. the carrying and moving tasks. This difference was more evident with the following risk measures: lifting Index (LI), probability

of membership in a group at high risk of a low back disorder (P_{RISK}), maximal L5/S1 external moments in the sagittal plane (M_{SAGITTAL}), and REBA.

Table 2. Regression models to predict risk measures for lifting and performance of each. Note: P_{RISK} is the probability of membership in a group at high risk of a low back disorder; M_{FRONTA} , $M_{TRANS.}$, and $M_{SAGITTAL}$ are maximal L5/S1 external moments in the frontal, transverse, and sagittal planes, respectively; and F_{AP} , F_{COMP} , and F_{LAT} are antero-posterior (AP) shear, compressive, and lateral shear reaction forces at the lumbosacral joint, respectively.

Lifting	Model	r^2	MAE	RMSE
Lifting Index (LI)	$0.085 + 0.033M + 0.019/H_o + 1/H_o^2 \times (-0.0041 + 0.000016M) - 0.0057M \times NW$	0.71	0.26	0.37
P_{RISK}	$1/(1+e^{-A})$ where $A = 1.9 + 0.03M - 4.8H_o - 1.3NW \times S - 0.0015M \times S$	0.87	0.08	0.11
$M_{FRONTAL}$ (Nm)	$13.66 + 0.1M + 5.99S + 1.59H_o + M \times (-0.13H_o + 1.46H_o^2) + 0.034S \times NW$	0.16	8.96	12.05
$M_{TRANS.}$ (Nm)	$18.31 - 0.13M - 0.52NW - H_o \times (15.09 - 0.25M - 2.49S) + 1/H_o^2 \times (0.001M - 0.013S) + 0.095NW \times S$	0.53	4.17	6.56
$M_{SAGITTAL}$ (Nm)	$176.07 + 1.79M - 189.63H_o^2 - 0.28M \times S + S \times (-87.65H_o + 90.4H_o^2) + 0.021M \times NW \times S$	0.76	25.04	32.05
F_{AP} (N)	$964.45 + 7.7M - 201.5S - 8.32M \times H_o$	0.25	276.52	366.12
F_{COMP} (N)	$3717.76 + 14.56M - 572.06S - 632.77H_o \times NW + 0.034M/H_o^2 + 75.81H_o \times S \times M$	0.43	703.28	894.19
F_{LAT} (N)	$72.73 + 4.94M - 105.37S - H_o \times (27.32NW + 6.85M - 172.44S) - 1/H_o^2 \times (0.0089M - 0.25S) - 0.02M \times NW \times S$	0.35	55.8	73.56
REBA	$9.46 - 9.41H_o^2 + M \times (0.0055NW - 0.20H_o) + H_o^2 \times (0.31M - 0.44/S) - 0.011M \times H_o \times NW$	0.87	0.63	0.83

Table 3. Regression models to predict risk measures for carrying, and performance, and performance of each.

Carrying	Model	r^2	MAE	RMSE
$M_{FRONTAL}$ (Nm)	$-8.55 + S \times (14.26 + 15.14NW) - 4.66NW/S^2 + 0.005 M \times NW \times S$	0.22	10.06	12.64
$M_{TRANS.}$ (Nm)	$3.98 + M \times (0.34 - 0.064NW - 0.065S) + 0.6NW/S^2$	0.20	4.01	4.97
$M_{SAGITTAL}$ (Nm)	$77.21 + NW \times (-16.32 + 3.06S) + 0.15M$	0.23	12.43	15.85
F_{AP} (N)	$646.31 + M \times (6.36 - 1.32NW) - 228.52S + 94.27S^2$	0.19	257.02	334.77
F_{COMP} (N)	$3040.18 + S \times (-135.91NW + 1.67S \times M)$	0.14	568.33	723.86
F_{LAT} (N)	$-510.73 + S \times (776.42 - 179.68S) + 0.85M$	0.07	169.35	239.47
REBA	$5.76 + M \times (-0.022 + 0.0077S + 0.0006NW) - 0.1S^2$	0.09	0.16	0.34

Table 4. Regression models to predict risk measures for erecting (E1Side), and performance of each.

E1Side	Model	r^2	MAE	RMSE
P_{RISK}	$1/(1+e^{-A})$ where $A = 1.56 + 0.077M - 6.75H_o - S \times (-0.023M + 1.67H_o^2)$	0.77	0.09	0.12
$M_{FRONTAL}$ (Nm)	$45.49 + M \times (1.22 - 0.35S) - 12.1H_o \times NW + 15.16S \times H_o^2$	0.16	16.45	20.95
$M_{TRANS.}$ (Nm)	$-33.96 + 29.87S + H_o \times (66.35 + 0.23M - 42.09S) - 0.014NW/H_o^2$	0.24	14.23	20.13
$M_{SAGITTAL}$ (Nm)	$380.89 + M \times (3.22 - 0.15NW - 0.71S) - 98.45S + H_o^2 \times (-1102.86 + 173.18S + 628.2H_o)$	0.80	29.83	38.6
F_{AP} (N)	$509.59 + M \times (-0.26 + 4.77NW + 3.8S) + 0.31NW/H_o^2 - 2.38M \times NW \times S$	0.22	268.5	351.93
F_{COMP} (N)	$1491.58 + M \times (69.3 - 3.71NW - 17.17S) + 277.61NW \times H_o + 0.053M/H_o^2$	0.60	684.17	865.94
F_{LAT} (N)	$824.56 - 210.34 - H_o \times (525.69NW + 4.54M - 150.08S) - 4.19M \times H_o^2 + 180.06S \times NW \times H_o^2$	0.41	114.41	172.58
REBA	$8.08 - 5.38H_o - 0.012/H_o^2 + M \times (-0.001NW + 0.022H_o) + 0.33/H_o - 0.0018M \times H_o \times NW$	0.93	0.51	0.64

Table 5. Regression models to predict risk measures for erecting (E1Top), and performance of each.

E1Top	Model	r^2	MAE	RMSE
P_{RISK}	$1/(1+e^{-A})$ where $A = 2.7 - H_o \times (5.86 + 0.5NW) + 0.056H_o^2 \times M - 0.0049M \times H_o \times NW$	0.89	0.08	0.12
$M_{FRONTAL}$ (Nm)	$-10.96 + 87.93H_o + 1/H_o^2 \times (-0.094 - 0.021NW + 0.02S) - 11.59H_o \times NW + 4.49/H_o + 0.0029M \times NW \times S$	0.15	13.4	18.2
$M_{TRANS.}$ (Nm)	$-0.66 + M \times (0.21 - 0.035NW) + 0.96/H_o - 1/H_o^2 \times (0.017 + 0.00028M - 0.0083S)$	0.39	6.04	7.88
$M_{SAGITTAL}$ (Nm)	$232.52 - 25.3NW + 0.55M + H_o^2 \times (-912.88 + 886.69H_o) + 0.02M \times NW \times S$	0.78	27.06	36.28
F_{AP} (N)	$1381.77 - 0.0059M - H_o \times (1598.2NW + 648.49S) + H_o^2 \times (4106.98 - 1654.6NW - 2784.05H_o) + 2.26M \times H_o \times NW$	0.22	310.07	401.22
F_{COMP} (N)	$5424.19 + NW \times (-731.2 + 4.12M) + S \times H_o \times (-3343.07 + 2884.02H_o) + 123.12S \times H_o \times NW$	0.36	799.37	1037.56
F_{LAT} (N)	$83.09 + M \times (0.37 + 0.2NW) + 35.49NW \times H_o - 28.44S \times H_o \times NW$	0.15	80.77	106.33

REBA	$8.64 + M \times (0.036 - 0.011S) - 8.29H_o^2 + 0.04S \times$ NW	0.93	0.56	0.70

Table 6. Regression models to predict risk measures for moving, and performance of each.

Moving	Model	r^2	MAE	RMSE
$M_{FRONTAL}$ (Nm)	$27.24 + 4.27NW + 0.03M \times S - 0.014M \times NW \times S$	0.1	14.16	19.09
$M_{TRANS.}$ (Nm)	$26.28 - 19.97S + 0.029M \times NW + 4.83/S$	0.18	5.08	6.35
$M_{SAGITTAL}$ (Nm)	$50.76 - 0.087M - 0.073M \times NW + 0.023M \times NW \times S$	0.01	16.49	26.87
F_{AP} (N)	$336.78 + 1.55S \times M - 5.82NW/S^2$	0.14	232.66	281.91
F_{COMP} (N)	$-112.25 + 1870.12S + 0.55M/S^2 - 154.5/S$	0.13	597.47	829.63
F_{LAT} (N)	$-1696.05 + 27.65M + S \times (1608.1 - 31.64M) + 7.23M/S^2 - 108.51/S + 0.15M \times S \times NW$	0.24	111.17	180.87
REBA	$5.47 + 0.001M - 0.05S \times NW$	0.03	0.54	0.73

3.2 Model performance using Study 2 data

Predicted LI values appeared to have a good association with true LI values (Table 7), though MAE and RMSE values were ~85% and ~50% larger, respectively, than those from the model development data set (Study 1). The models for REBA appeared to have limited predictive value, and which contrasts the finding on REBA above. Analysis and validation of the models for the models for other risk measures is still in process.

Table 7. Validation performance of the developed models for LI and REBA

Task	Risk measure	r^2	MAE	RMSE
Lifting	LI	0.74	0.48	0.55
	REBA	0.14	1.95	2.47
E1Side	REBA	0.17	1.36	1.69
E1Top	REBA	0.12	3.03	3.4
Moving	REBA	0.01	1.43	1.75

3. Discussion

This study aimed to develop prediction models to obtained risk measures for WMSDs (particularly low back disorder) during diverse panel installation tasks, using specific task-based parameters (i.e., panel mass, size, origin height and/or the number of workers) as predictors. Model development and validation were completed with datasets from two separate experiments. The model development results suggested that solely using these task-based parameters can be effective at quantifying a few risk measures for lifting and erecting tasks, such as LI, P_{RISK} , $M_{SAGITTAL}$, and REBA. However, when considering LI and REBA, the predictive validity of only LI was supported.

The task-based predictors considered here appeared important in quantifying a few risk measures (i.e., LI, P_{RISK} , M_{SAGITTAL} , and REBA) for the lifting and erecting tasks (Tables 2, 4, and 5) compared to the carrying and moving tasks (Tables 3 and 6). The model development results showed that predicting such measures for the lifting and erecting tasks yielded a rather high r^2 value (>0.7), and some variation in the magnitude of errors given RMSE values are generally larger than MAE values (though not substantially). However, only the model for LI was found to have a reasonable predictive ability, considering the r^2 value (0.71). MAE and RMSE values increased about 85% and 49% compared to those from Study 1, and which suggests that a change in predicted LI values is more practically meaningful than actual values. REBA prediction models performed quite poorly (e.g., r^2 values < 0.2). REBA is essentially a posture-based analysis, so poor performance could be attributed to a large variation in work strategies (i.e., different motions and postures) for a given task. Thus, one possible solution to improve REBA predictions can be to incorporate other predictors that reflect working methods, such as hand locations and panel origin height relative to the participant's stature.

For the carrying and moving tasks, our results suggest that the current task-based predictors are not sufficient in quantifying the risk measures. This could mean that variance in the risk measures is more affected by individual differences (e.g., work strategies, strength) than by the task-based parameters, as well as a possible need to consider task-based parameters beyond the current ones. Earlier studies on carrying tasks have indicated that carrying speed affects variability in the ground reaction forces (Hsiang & Chang, 2002), and that the trunk inclination angle can affect the level of low back loading (Visser et al., 2015). Carrying speed and task-based parameters that can reflect the trunk inclination angle may thus have value in improving predictions. Further, Hoozemans et al. (2004) demonstrated the potential of their regression model for pushing and pulling tasks, to predict low back and shoulder loading with task-based parameters (e.g., cart mass, hand location), though the predictive validity of their model was not examined. Therefore, it may also be of value to incorporate hand location and possible potential predictors (e.g., stature, strength) for the moving task to capture differences in work strategies during moving tasks.

Work in progress

The current results supported that some risk measures can be quantified and/or predicted for some panel installation tasks such as lifting and erecting, using the task-based predictors. Nonetheless, a clear need also exists for further investigation of possible potential parameters that can reflect individual differences and task characteristics, to improve prediction performance. As discussed above, such parameters can be hand location, variables to describe trunk inclination angles (e.g., max, SD), carrying speed, and individual factors (e.g., stature, body mass, grip strength). To facilitate the use of the developed model in simulation modeling, these parameters could be considered as categorical. In addition, given only linear regression was used in the current study and that an effective model was not defined for all the tasks and risk measures, we could explore alternative data “mapping” approaches such as artificial neural networks (ANN), fuzzy regression, fuzzy regression with ANN, and others.

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4. Development and Operation of the Decision Support System

4.1. A lean approach to organizing and location stacks in panelized construction

Shewchuk J, Guo C: [2012] Panel stacking, panel sequencing, and stack locating in residential construction: lean approach, Journal of Construction Engineering and Management 138:1006-1016.

ABSTRACT

A current trend in residential construction is the use of prefabricated wall panels. Panels are manufactured at a factory, then arranged into stacks for transporting to the construction site, where they are assembled. Current approaches to planning panelized construction are focused on stacking and transport efficiency, with little consideration given to assembly. This results in excessive panel material handling during construction, increased construction lead time, and increased risk of worker overload and/or injury. This paper proposes a lean approach to panel stacking, panel sequencing and stack locating, where panels within each stack form a continuous structure and are erected via continuous flow. The objectives are to minimize the quantity of stacks, panel material handling distance, and the work required to position and brace panels: panel interference is ignored. Few researchers have addressed this problem: a single algorithm has been reported, and this only works for certain building shapes and may provide infeasible solutions. The proposed approach and algorithm result in improved performance, have no shape restrictions, and always provide feasible solutions. Additionally, computational experiments show that the algorithm outperforms methods being employed in the construction industry today.

INTRODUCTION

Residential construction using prefabricated walls is becoming an established trend in the United States and abroad. In this approach, wall sections ('panels') are fabricated at a factory, then transported to the construction site for assembly. The approach offers many advantages over traditional, 'stick-built' construction. Quality is vastly improved, as panels can be fabricated in manufacturing facilities using tools, techniques, jigs, and fixtures unavailable at the construction site. Additionally, both the time to produce panels and the on-site construction time can be decreased dramatically, as can the amount of material needed. A study by the Building Systems Council (National Association of Home Builders, 2009) reports that construction of a 2,600 sq. ft. home with trusses and panels took just 37% of the man-hours needed for a stick-built home, and also used 26% less lumber and generated 76% less waste. Panelized construction also reduces the need for skilled labor and the risk of on-site theft of materials (Shepherd, 2000).

The first step in the panelized residential construction process is to come up with a *panelization plan*, which specifies how to divide the walls of a building into panels. The panel manufacturer produces the panels and arranges them into one or more *stacks* for shipment to the construction site. Upon arrival, each stack is dropped at some location on the structure floor.

Workers unbind the stack, then each panel in the stack is carried to its final location in the structure, erected (tipped upright), positioned, braced (to keep it from falling), and ultimately attached to the other panels to form a continuous structure.

An important part of the panelized approach is the initial planning stage following panelization, where the panel manufacturer must figure out what panels go into each stack and how they should be arranged. Furthermore, the stack drop-off locations on the structure floor must be determined, as must the sequence in which the workers will install the panels found in each stack. Current approaches to these problems are focused on stacking, with the objective typically being to minimize the quantity of stacks so that they can be taken to the site with the fewest trips possible. Drop-off locations are typically at the discretion of the driver of the delivery truck, with stacks dropped off at the easiest locations to get to, even though such locations may significantly increase the distance workers must move panels. Finally, little consideration is given to how construction will proceed once the stacks are delivered. The construction foreman or lead hand must determine the construction sequence for each stack, with little more to go on than his/her own experience. Whatever sequence is selected, the arrangement of panels in the stack invariably causes problems. Workers must routinely remove one or more panels from a stack to get to the one they want: removed panels are moved off to the side (necessitating additional material handling) or simply left on the floor (creating a safety hazard). Further material handling is incurred walking around panels left on the floor. Panels which do not connect with any completed panels, but are easily accessible in the stack, are often moved directly to their final locations and erected. Such panels, being freestanding, require substantial temporary bracing in order to remain upright until they can be permanently attached to other panels. In other cases, using easily-accessible panels first results in problems for downstream panels when the former blocks or otherwise restricts access for the latter. Overall, the current approach to panel stacking, panel sequencing, and stack locating results in not only excessive construction time, but also increased safety hazards and increased risk of worker injury and overload.

In this paper, we propose an approach to panel stacking, panel sequencing, and stack locating aimed at addressing these problems. The approach is based upon lean manufacturing, which has revolutionized manufacturing worldwide (Womack and Jones, 2003) and has more recently made inroads into the construction field (e.g., Construction Industry Institute 2005, Sharma *et al.* 2006, Watkins *et al.* 2009). In order to focus on maximizing performance (e.g., minimize panel material handling distance), panel interference is intentionally ignored. This refers to both *unload interference* (a panel cannot be unloaded without hitting a finished panel already in place) and *stack interference* (the stack overlaps all or part of a panel's final location in the structure). Relevant literature is reviewed first, followed by a detailed description of the problem and discussion of objectives. The proposed approach is then presented, followed by a detailed exposition of the corresponding algorithms. Computational experiments are described, and results presented and discussed. Finally, concluding remarks are provided, along with a discussion of where additional research is needed. The notation used throughout the paper is presented at the end.

LITERATURE REVIEW

A review of the literature has found only two items concerned with the panel stacking, panel sequencing and/or stack locating problems in residential construction using panelized walls. Shewchuk *et al.* (2009) present a framework for tackling the problems in a lean context. The structure floor plan is divided into a set of non-overlapping zones, and the problems then solved on a zone basis. This 'zone approach' guarantees that unload interference does not occur, but performance (total panel move distance and quantity of stacks) suffers as a result. Guo (2010) also tackles the panel stacking, panel sequencing, and stack locating problems using the zone approach. A second approach is also presented, where the problems are solved directly (no zone constraints exist). Unlike the zone approach, the focus is on maximizing performance: both unload and stack interference are ignored. The algorithm presented suffers from several shortcomings, however: it requires the edge of the structure along which the panels are dropped to be straight, and can result in infeasible solutions when installing exterior panels. Furthermore, the approach and algorithm are evaluated by approximating the stacking problem as a two-dimensional cutting stock problem, limiting the validity of the results. This paper follows this second approach (maximum performance, worry about interference later) and addresses each of these shortcomings.

Besides these items, the most closely-related papers are those dealing with layout planning, lean construction, and construction process planning. Jang *et al.* (2007) propose a floor-level construction material layout to minimize repositioning construction materials, using a genetic algorithm to tackle the problem. They report that their approach reduces material handling time. But they consider elements such as crane location only: panel stacking and stack locations are not addressed. Hegazy *et al.* (1999) present a model and genetic algorithm for layout planning which "places facilities" at a construction site. They assume that panels are stacked when they are delivered to the construction site, and hence do not address the panel stacking problem.

In the area of lean construction, Beary and Abdelhamid (2005) developed a production planning model based on Lean Construction production planning concepts and Six Sigma techniques. It was reported that Lean Construction aims at identifying and eliminating waste and that continuous improvement is needed. The issue of panel stacking, however, is not addressed. Choo *et al.* (1999) created a database program which implemented several lean construction techniques to help crew foreman to allocate available and equipment resources. But again, the panel stacking problem was not examined. Zhang *et al.* (2005) propose replacing the traditional management approach for residential construction site operation with a management philosophy that has as its sole and unifying objective the elimination of process waste. But this paper does not consider stacking at all: waste refers only to missing or broken tools/equipment, missing information, improperly staged material, and incomplete prior work.

Several authors have investigated automatic generation of construction process plans. Hu (2005) presented a model based on geometric reasoning, which reverses the disassembly process to obtain the construction process. The model provides a graph of precedence constraints, thus allowing feasible construction sequences to be established. But the related issue of how the panels should be stacked (for any given sequence) is not addressed: this is left for construction workers in the field. Nguyen and Oloufa (2001) developed a building design

methodology, via a solid modeling platform, which can generate complex building information. Nguyen (2005) then proposes a framework that can generate sequences of construction activities automatically. But the framework is limited to the use of spatial information to establish construction sequences: other factors such as work spaces, panel stacking, and stack locations are not considered.

In summary, several related papers provide useful background for tackling the panel stacking, panel sequencing, and stack locating problems, but only two tackle the problem directly and these have shortcomings which limit their applicability.

PROBLEM DESCRIPTION

Figure 1 shows a plan view of a hypothetical panelized structure. Throughout this paper, we refer to the top, bottom, left, and right side of the structure with respect to this plan view. Additionally, we defined each panel as being either horizontal or vertical, depending upon how it appears in this view (e.g., panel 15 is horizontal, panel 18 is vertical). As shown in Figure 2, all panels within each stack are similarly oriented (all wall studs run in the same direction in the stack) and are of the same height. While stacks may vary in height and length, there will be some maximum stack height beyond which workers cannot safely remove panels and the stacks themselves become unstable. Additionally, there will be some maximum stack length beyond which the stack cannot be easily transported and also becomes too big to work with. Stacks are dropped off sequentially, with each placed directly on the sub-floor of (as opposed to being placed beside) the structure. This is necessary for workers to safely move panels from the stack to a location within the structure. Finally, all stacks are dropped off with their length dimension (bottom plate, top plate) parallel to and one length edge flush with some edge of the structure, and the stack sides cannot overlap the structure edges. Each of these assumptions reflects current practice, as verified through discussion with panel manufacturers and/or observations of actual panelized wall construction.

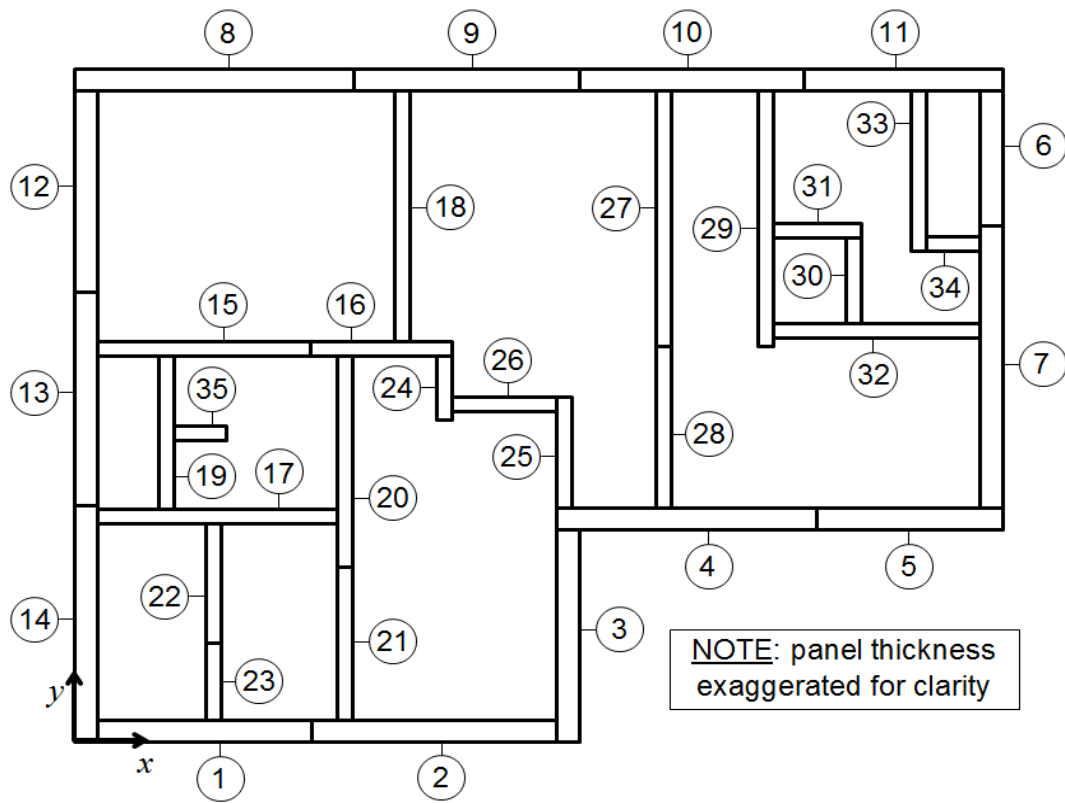


Figure 1. Example panelized building structure (35 panels).

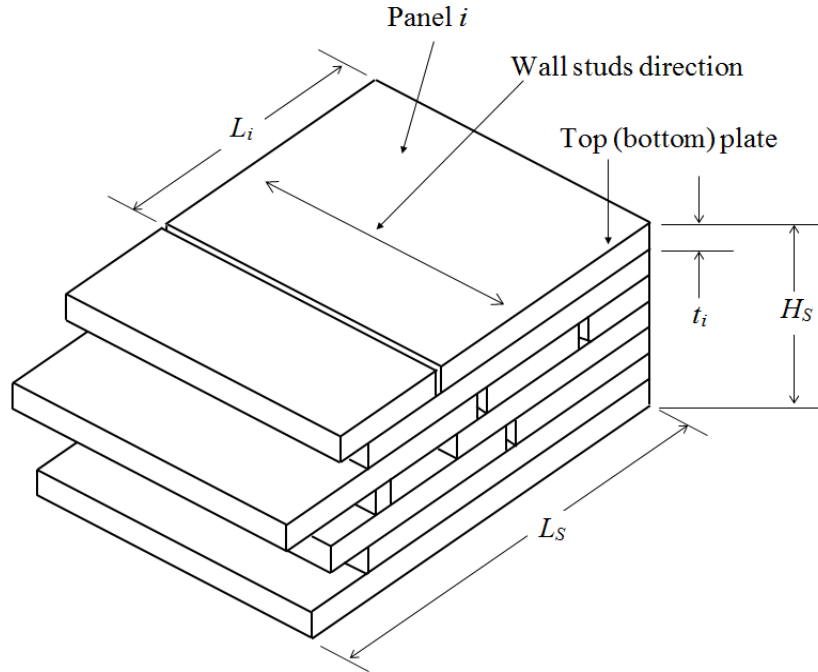


Figure 2. Example stack for panelized residential construction.

Given a panelization plan, maximum stack length, and maximum stack height, the objective is to find (i) what panels go into each stack and how they are arranged into layers, (ii) the construction sequence for the panels in each stack, and (iii) stack drop-off locations.

OBJECTIVES

As previously discussed, the current emphasis in residential panelized construction is on efficient stack formation at the factory and minimizing the quantity of trips to the job site. One obvious objective is thus to minimize the quantity of stacks, as this results in the fewest trips (all other factors being equal). The high prevalence of occupational injuries sustained by workers in panelized construction, however, points to the need to factor ergonomic considerations into the design process. Along these lines, we propose three additional objectives aimed at making the process both more efficient and safer for the workers.

The first of these is to minimize the total effort needed for workers to carry the panels from stacks to final locations in the structure. While this depends upon worker path preferences, move methods, obstacles, and other factors unknown at this stage of planning, it first and foremost depends upon the rectilinear distance from the panel's starting location (stack centroid) to its final location in the structure. Additionally, we must somehow account for the fact that larger panels will be more difficult to move, both due to increased size (making navigation and clearing obstacles more difficult) and weight. For simplicity, we simply use panel

length as a multiplier to account for these facts. Thus, we can calculate *total weighted panel material handling distance*, WMH , as follows:

$$WMH = \sum_{k=1}^M \sum_{i \in S_k} L_i \cdot (|x_i - u_k| + |y_i - v_k|) \quad (1)$$

The second objective is to minimize the work needed to position each panel (jog, slide, or other fine movement) at its final location once it has been erected. While this depends upon positioning methods, tools available, etc., it first and foremost depends upon the how well the panels ‘fit together’ during construction. Figure 3(a) and (b) shows examples of ‘good’ and ‘bad’ panel fit scenarios: in the latter case, panel i must be ‘squeezed’ between multiple panels. The work required to position panel i is minimized when a ‘good’ fit scenario exists: we say that each such panel i exhibits *fittability*. An overall measure of fittability is

$$FIT = \sum_{i=1}^N f_i / (N - Q) \quad (2)$$

where f_i = fittability of panel $i = 1$ if the panel encounters a ‘good’ panel fit scenario, 0 otherwise; Q = quantity of panels which can never exhibit fittability (last exterior panel or last interior panel of any wall spanning exterior panels, e.g. panel 27 or 28, Figure 1).

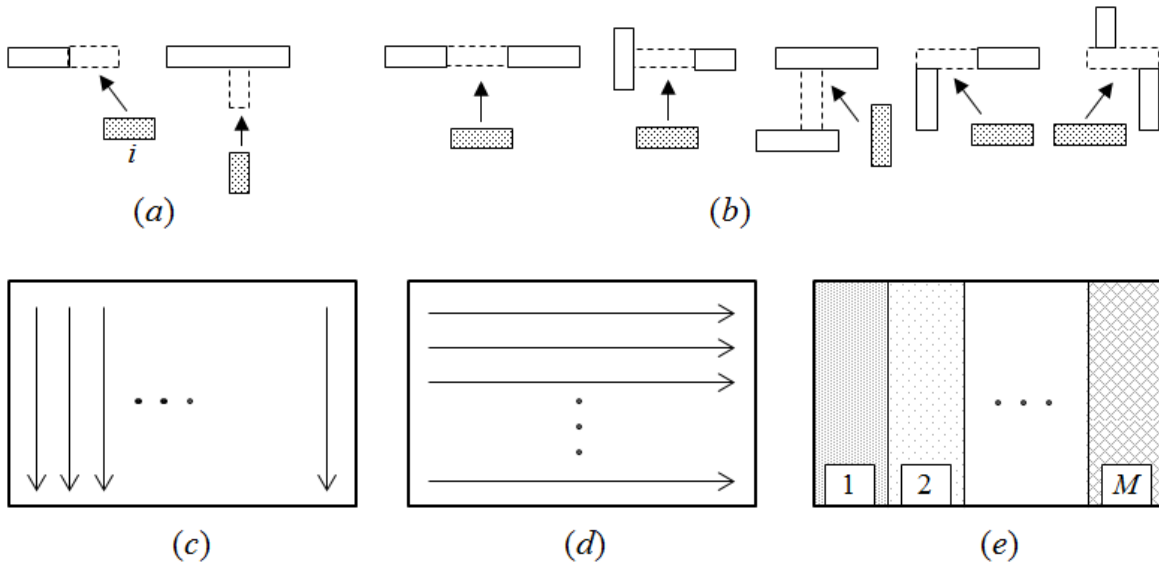


Figure 3. (a) ‘Good’ panel fit scenarios, (b) ‘Bad’ panel fit scenarios, (c) Top-to-bottom build pattern, (d) Left-to-right build pattern, (e) Stack arrivals, panels resulting in vertical ‘stack areas.’

The third objective is to minimize the work required to brace each panel following positioning, so that it remains upright. Again, this depends upon several factors not established at this stage, but at the most basic level the work is minimized when panel i connects to (joins with) one or more panels already in place. The panel can then be directly fastened to the other panel(s) with minimal bracing: substantial additional bracing may be required otherwise. Each such panel i exhibits *connectivity*. Noting that the first panel installed can never exhibit connectivity, an overall measure of connectivity is

$$CONN = \sum_{k=1}^M \sum_{i \in S_k} c_i / (N-1) \quad (3)$$

where c_i =connectivity of panel $i = 1, |\mathbf{conn}_i \cap (\mathbf{S}_1 + \mathbf{S}_2 + \dots + \mathbf{S}_{k-1} + \{s_{k[1]}, s_{k[2]}, \dots, s_{k[n-1]}\})| > 0, 0$ otherwise; $s_{k[j]} = j^{th}$ panel in sequence $\mathbf{S}_k$, and $n = j \mid s_{k[j]} = i$.

APPROACH

The proposed approach to panel stacking, panel sequencing, and stack locating is based upon the following lean concepts:

- i) Panels are always taken in the order in which they appear in the stack. In other words, the top panel of each stack (or one of the panels on the top layer, if multiple panels are present) is always the next one needed. Workers no longer slide panel after panel off to the side, onto the floor, etc., to get to the panel they need. Only those panels being worked on are out of the stack, and the work area is kept neat and tidy (lean principle: 5S). This not only accelerates construction: it also eliminates the safety hazards resulting from panels left lying on the ground, tipped against walls, etc.
- ii) Once a panel is removed from a stack, it is processed in one continuous operation until it is fixed at its final position in the structure (lean principle: continuous flow).
- iii) Panels must be installed quickly and correctly the first time (lean principle: jidoka).

The proposed approach is as follows. Stacks are dropped off along a single edge of the structure: this is referred to as the *dropping edge*. At least one edge must be accessible for stack drop-off: using one edge only allows the delivery procedure to be simplified and standardized. To simplify the algorithm, the bottom edge (e.g., panels 1-5 in Figure 1) is always taken as the dropping edge. The overall panel construction sequence is established first: each exterior panel must be put in place before any of its connecting interior panels. Additionally, construction progresses both left-right (by convention) and top-bottom (so that the stack area is kept clear as long as possible). The use of these two preferred *construction directions* ensures

connectivity and fittability are maximized, which makes it possible to install panels quickly and correctly the first time.

The preferred construction directions can be achieved in two different ways: by building *top-to-bottom* (Figure 3c) or *left-to-right* (Figure 3d). We refer to each of these as a *build pattern*. Top-to-bottom is used to assign panels to stacks: this results in stacks whose panels more or less fill a series of vertical ‘stack areas,’ starting with the left edge of the structure and progressing to the right edge (Figure 3e). This tight clustering of panels around each stack keeps material handling distances small. Left-to-right is then used to sequence the panels in each stack: this delays the top-bottom movement (and thus preserves stack accessibility) as long as possible. To ensure that the panels in each stack can be used in the order provided, whatever the sequence, we allow each stack to consist of both exterior and interior panels. Furthermore, we allow panels of different thickness (e.g., 2x6 in. exterior panel vs. 2x4 in. interior panel) to be located in the same stack layer: spacers can be used to ensure the layers remain parallel in such cases. This allows exterior and interior panels to share the same layer, maximizing space utilization in the stack and minimizing stack quantity. Finally, we assume that only one stack is on the structure at a time. This allows drop-off locations to overlap, if necessary, allowing the best possible location to be established for each.

Note that the above approach considers a single dropping edge and set of preferred construction directions (left-right, top-bottom). In practice, the approach should be tried with each accessible dropping edge, as well as the other preferred construction directions. Different dropping edges can be obtained by simply rotating the panelization plan. Additionally, (i) a right-left construction direction can be obtained by mirroring the panelization plan about the central vertical axis; (ii) a bottom-top construction direction can similarly be obtained by mirroring about the central horizontal axis.

ALGORITHM

The above approach is realized via an iterative algorithm consisting of six stages (Figure 4). Procedures for each of these stages are described in detail below. To aid in understanding the algorithm, an example problem will be solved. This consists of the structure of Figure 1 ($t_i = 6$ in. for exterior panels, 4 in. for interior panels) and $H_{S,\max} = 60$ in., $L_{S,\max} = 135$ in.

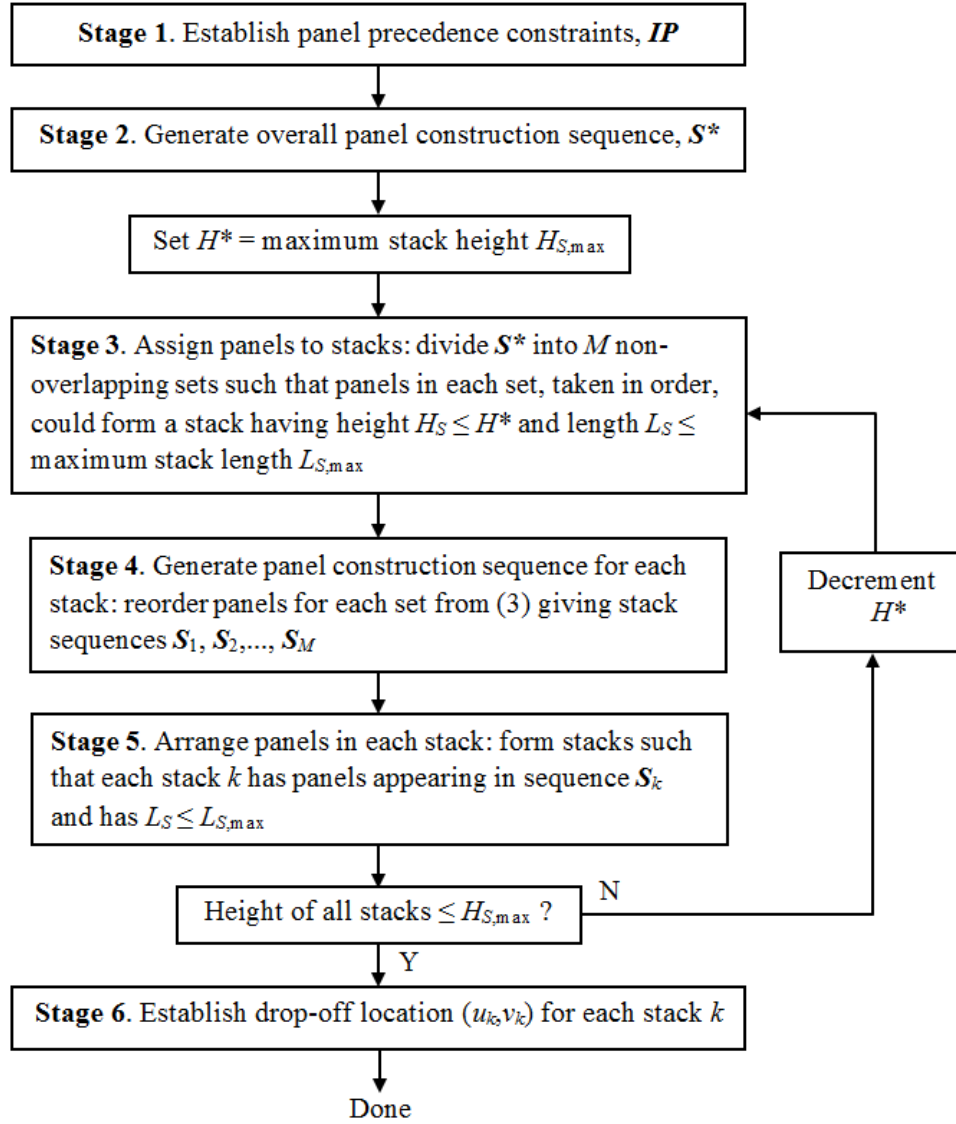


Figure 4. Overall approach to panel stacking, panel sequencing and stack locating.

Stage 1: Panel Precedence Constraints

Though there are many possible ways to construct a panelized structure (and hence many sets of feasible precedence constraints), a single set of constraints is possible given that (i) each exterior panel must be put in place before any of its interior connecting panels, (ii) all panels (except the first) exhibit connectivity, and (iii) the given build pattern is followed, unless this violates (ii). Exterior panels are handled separately from interior panels: the two procedures are as follows.

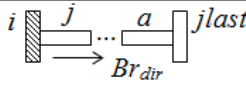
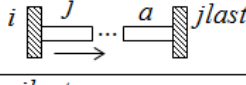
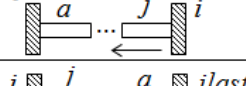
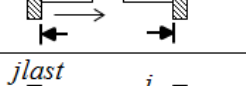
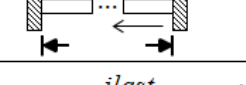
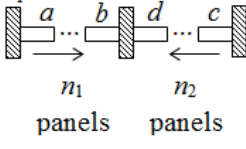
I) Exterior panel precedence constraints

To establish exterior panel precedence constraints, we start by identifying the first exterior panel FP and last exterior panel LP . Using a left-to-right build pattern, these are the top left corner panel and bottom right corner panel, respectively. Starting with FP , we move clockwise around the exterior to LP , recording precedence for each pairs of panel. The process is then repeated, but moving counterclockwise. For the example structure (Figure 1), $FP = 8$ and $LP = 5$ (throughout this paper, bold font is use to denote exterior panels and regular font interior panels). Clockwise rotation from FP results in $IP = \{(8,9), (9,10), (10,11), (11,6), (6,7), (7,5)\}$. Counterclockwise rotation then results in $IP = \{(8,12), (12,13), (13,14), (14,1), (1,2), (2,3), (3,4), (4,5)\}$.

II) Interior panel precedence constraints

Interior precedence constraints are formed by recursively constructing branches, again using a left-to-right build pattern, and setting precedence constraints one branch at a time. The procedure is detailed below: the function $LtoR(F)$ sorts the panels in set F following a left-to-right build pattern.

0. Initialize. Set $F = \text{set of exterior panels} = \{i \in 1, \dots, N \mid b_i = 1\}$. Then sort these panels: $F^* = LtoR(F)$. Mark all exterior panels as assigned and interior panels as unassigned, set $T = \text{temporary storage array} = \{\}$, $m = 1$.
1. Let $i = m^{th}$ panel in F^* . Find the set of panels which connect with panel i but currently have no precedence relationship with this panel = $B = \{j \in \text{conn}_i \mid (i,j) \notin IP, (j,i) \notin IP\}$. If $|B| = 0$, go to step 4; else find $B^* = LtoR(B)$, set $n = 1$.
2. Construct the branch starting with root panel i and having first branching panel j , where $j = n^{th}$ panel in B^* . Branching is illustrated in Figure 5: each branch continues in the direction of panel j and ends with panel j_{last} , which is either an unassigned (and hence terminal) panel (Figure 5a) or an already-assigned panel (Figure 5b). Precedence relationships are then established for each successive pair of panels moving in the branch direction, the set of unassigned panels is stored as **bpanels**, and each of these unassigned panels is then assigned. In the event that the last panel in the branch is already assigned, four special cases are possible, depending upon the branch direction and how the first and last panels are constrained in the structure. These cases are shown in Figure 5c-f.
3. Add branch panels to T : $T \leftarrow T + \text{bpanels}$; add precedence constraints to IP . If $n < |B^*|$, more branches remain for root panel i . Set $n \leftarrow n + 1$, go to step 2.
4. If $m < |F^*|$ more root panels remain for current panel set F^* . Set $m \leftarrow m + 1$, go to step 1.
5. All branches have been formed for all root panels in the current panel set F^* . If $|T| > 0$, form the next set of root panels: set $F^* = LtoR(T)$. Then set $T = \{\}$, $m = 1$, go to step 1. Else done.

Branching scenario ¹	Result ²	Branch construction ³
(a)  $A_{jlast} = 0, Br_{dir} = P_{dir}$	Standard branch	$i \rightarrow [j] \rightarrow \dots \rightarrow [a] \rightarrow (jlast)$
(b)  $A_{jlast} = 1, Br_{dir} = P_{dir}$	Standard branch	$i \rightarrow [j] \rightarrow \dots \rightarrow [a] \rightarrow jlast$
(c)  $A_{jlast} = 1, Br_{dir} \neq P_{dir}$	Reverse Br_{dir}	$i \leftarrow [j] \leftarrow \dots \leftarrow [a] \leftarrow jlast$
(d)  $A_{jlast} = 1, Br_{dir} = P_{dir}$, panels i and $jlast$ both constrained	Squeeze fit 2 nd last panel in branch (= a)	$i \rightarrow [j] \rightarrow \dots \rightarrow [a] \leftarrow jlast$
(e)  $A_{jlast} = 1, Br_{dir} \neq P_{dir}$, panels i and $jlast$ both constrained	Reverse Br_{dir} , squeeze fit panel j	$i \rightarrow [j] \leftarrow \dots \leftarrow [a] \leftarrow jlast$
(f)  $jlast$ part of two branches, 'sandwich panel' results: $n_1 = n_2 = 1$ $n_1 > 1$ $n_1 = 1$	Fix panelization plan Squeeze fit panel b Reverse #2 Br_{dir} , squeeze fit panel c	$i_1 \rightarrow [a] \rightarrow \dots \rightarrow [b] \leftarrow jlast$ $i_2 \rightarrow [c] \rightarrow \dots \rightarrow [d] \rightarrow jlast$ $i_1 \rightarrow [a] \rightarrow \dots \rightarrow [b] \rightarrow jlast$ $i_2 \rightarrow [c] \leftarrow \dots \leftarrow [d] \leftarrow jlast$

¹Each scenario shown is representative of many possible cases. Any joint type (T, butt, corner) is possible between panels: the branches can also be vertical. $A_n = 1$ if panel n already assigned, 0 otherwise; Br_{dir} = branching direction, P_{dir} = preferred build direction.

²Whenever branching direction reversed, reverse back if cycling occurs.

³ n : panel n already assigned, $[n]$: panel n may or may not be already assigned, (n) : panel n not assigned.

Figure 5. Branching scenarios.

Figure 6 shows the application of the above algorithm to the example problem. Examples of branching scenario (a) from Figure 5 are branches $9 \rightarrow (18) \rightarrow (16)$ and $14 \rightarrow (17) \rightarrow (20)$: branching scenario (b) can be seen via $7 \rightarrow (32) \rightarrow 29$ and $13 \rightarrow (15) \rightarrow 16$. An example of special case (c) is provided by branch $25 \leftarrow (26) \leftarrow 24$: the branch direction is reversed. Branch $32 \rightarrow (30) \rightarrow 31$ also satisfies special case (c): reversing this branch results in a cycle ($29 \rightarrow 31 \rightarrow (30) \rightarrow 32 \rightarrow 29$), however, so the branch direction is reversed back. Branch $10 \rightarrow (27) \rightarrow (28) \leftarrow 4$ is an example of special case (d): a squeeze fit is needed for panel 28. An example of special case (e) is provided by branch $2 \rightarrow (21) \leftarrow (20) \leftarrow 16$. Finally, branches $1 \rightarrow (23) \rightarrow (22) \rightarrow (17)$ and $15 \rightarrow (19) \rightarrow 17$ satisfy special case (f): the former thus becomes $1 \rightarrow (23) \leftarrow (22) \leftarrow (17)$.

i	B	B^*	n	branch ¹	$bpanels$	precedence constraints added
Step 0: $F = \{1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14\}$ $F^* = \{8, 9, 10, 11, 12, 6, 7, 13, 14, 4, 5, 3, 1, 2\}$, $T = \{ \}$						
9	{18}	{28}	1	$9 \rightarrow (18) \rightarrow (16)$	{18,16}	(9,18), (18,16)
10	{27,29}	{27,29}	1	$10 \rightarrow (27) \rightarrow (28) \leftarrow 4$	{27,28}	(10,27), (27,28), (4,28)
			2	$10 \rightarrow (29)$	{29}	(10,29)
11	{33}	{33}	1	$11 \rightarrow (33)$	{33}	(11,33)
7	{32,34}	{34,32}	1	$7 \rightarrow (34) \rightarrow 33$	{34}	(7,34), (34,33)
			2	$7 \rightarrow (32) \rightarrow 29$	{32}	(7,32), (32,29)
13	{15}	{15}	1	$13 \rightarrow (15) \rightarrow 16$	{15}	(13,15), (15,16)
14	{17}	{17}	1	$14 \rightarrow (17) \rightarrow (20)$	{17,20}	(14,17), (17,20)
4	{25}	{25}	1	$4 \rightarrow (25)$	{25}	(4,25)
1	{23}	{23}	1	$1 \rightarrow (23) \rightarrow (22) \rightarrow 17$	{23,22}	(1,23), (23,22), (22,17)
2	{21}	{21}	1	$2 \rightarrow (21) \leftarrow 20 \leftarrow 16$	{21}	(2,21), (20,21), (16,20)
Step 5: $T = \{18, 16, 27, 28, 29, 33, 34, 32, 15, 17, 20, 25, 23, 22, 21\}$ $F^* = \{18, 27, 29, 33, 34, 32, 15, 16, 28, 20, 25, 17, 22, 21, 23\}$, $T = \{ \}$						
29	{31}	{31}	1	$29 \rightarrow (31)$	{31}	(29,31)
32	{30}	{30}	1	$32 \rightarrow (30) \rightarrow 31$ (c)	{30}	(32,30), (30,31)
15	{19}	{19}	1	$15 \rightarrow (19) \rightarrow 17$	{19}	(15,19), (19,17)
				$1 \rightarrow (23) \rightarrow (22) \rightarrow 17$ becomes $1 \rightarrow (23) \leftarrow (22) \leftarrow 17$; (23,22) becomes (22,23) (f) (22,17) becomes (17,22)		
16	{24}	{24}	1	$16 \rightarrow (24)$	{24}	(16,24)
25	{26}	{26}	1	$25 \leftarrow (26) \leftarrow 24$ (c)	{26}	(26,25), (24,26)
Step 5: $T = \{31, 30, 19, 24, 26\}$ $F^* = \{31, 30, 19, 24, 26\}$, $T = \{ \}$						
19	{35}	{35}	1	$19 \rightarrow (35)$	{35}	(19,35)
Step 5: $T = \{35\}$ $F^* = \{35\}$						
-						

¹ n : panel n already assigned, (n): panel n not assigned.

Figure 6. Interior panel precedence constraints algorithm applied to example problem (**bold** = exterior panels).

The above two algorithms result in a total of 45 panel precedence constraints for the example problem. These are shown in the precedence diagram of Figure 7.

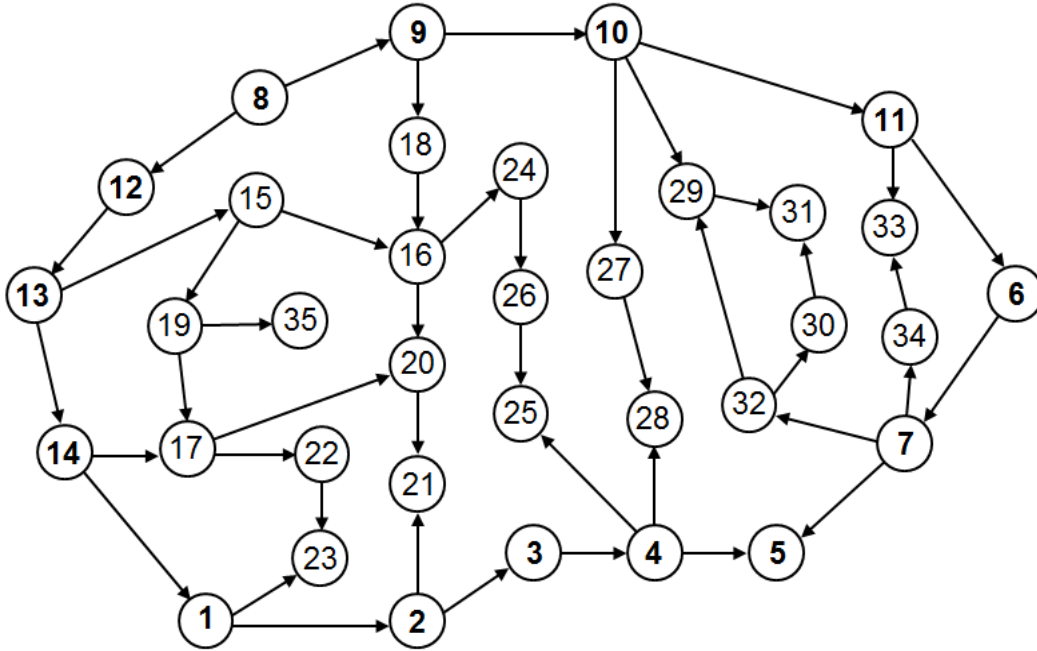


Figure 7. Precedence diagram generated for example problem (**bold** = exterior panels).

Stage 2: Overall Panel Construction Sequence

The overall panel construction sequence is generated by repeatedly forming the set of panels that are not yet assigned but have all of their predecessors assigned, then selecting a panel from this set. Vertical exterior panels are given priority, so that whenever a vertical wall is started, all panels in the wall are put up in uninterrupted sequence. This aids in enclosing the working space as quickly as possible. When no vertical exterior panels are present, the goal is to select panels using a top-to-bottom build pattern, so that any subset of panels in the overall sequence will result in a vertical stack area as previously described (Figure 3e). Horizontal panels connected at their right edge to vertical exterior panels must be handled separately, however, as these must be built right-left (because the exterior panel must come first). The procedure is shown in detailed below: the function $TtoB(F)$ sorts the panels in set F following a top-to-bottom build pattern.

0. Initialize. Set $S^* = \text{overall panel construction sequence} = \{FP\}$.
1. Determine the initial set of candidate panels for the next assignment = $C = \{j \mid j \notin S^*, i \in S^* \forall (i,j) \in IP\}$.
2. Find the subset of C having vertical exterior panels only = $V = \{j \mid j \in C, b_j = d_j = 1\}$. Note that there can be at most one such panel, due to precedence constraints.
3. If $|V| = 1$, set $m = \text{first panel in } V = V_{[1]}$; go to step 6.

4. Find the subset of $\mathbf{C}$ consisting of horizontal interior panels which have their right edge connecting to an exterior panel = $\mathbf{H} = \{j \mid j \in \mathbf{C}, b_j = 0, b_k = 1 \ \forall k \in \text{conn}_{j,R}\}$.

$$\sum_{i \in \mathbf{C}} (1 - b_i) = |\mathbf{H}|$$

If $i \in \mathbf{C}$, select from $\mathbf{H}$ the panel having the maximum y -coordinate: $m = \arg \max_j \{y_{edge_j}, j \in \mathbf{H}\}$; go to step 6.

5. Sort the panels in $\mathbf{C}$ using a top-to-bottom build pattern: $\mathbf{C}^* = TtoB(\mathbf{C})$. Then take the first panel from this set: $m = c^*_{[1]}$, where $c^*_{[k]} = k^{\text{th}}$ panel in $\mathbf{C}^*$.
6. Add panel m to the sequence: $\mathbf{S}^* \leftarrow \mathbf{S}^* + m$. If $|\mathbf{S}| = N$, done; else go to step 1.

Application of the above to the example problem results in the following. Following selection of the first panel ($m = 8$), we have $\mathbf{C} = \{9, 12\}$ and $\mathbf{V} = \{12\}$, giving $m = 12$. Vertical exterior panels 13 and 14, interior panel 15, and horizontal exterior panel 1 are similarly selected. At this point, we find $\mathbf{C} = \{2, 9, 19\}$, $\mathbf{C}^* = \{19, 2, 9\}$, and $m = 19$. Panels continue to be selected via $\mathbf{V}$ or $\mathbf{C}^*$ until the 29th panel, where $\mathbf{C} = \{5, 32, 34\}$, $\mathbf{H} = \{32, 34\}$, $m = 34$. Panel selection then continues via $\mathbf{C}^*$ only until the last panel, $m = 33$. The resulting panel construction sequence is $\mathbf{S}^* = (8, 12, 13, 14, 15, 1, 19, 17, 35, 22, 23, 2, 3, 9, 18, 16, 20, 21, 24, 26, 4, 25, 10, 27, 28, 11, 6, 7, 34, 32, 29, 5, 30, 31, 33)$.

Stage 3: Assignment of Panels to Stacks

Panels are assigned to stacks by dividing $\mathbf{S}^*$ into a succession of non-overlapping sets. Each set of panels then constitutes a stack. If the panels in each stack were then erected in order, connectivity would be guaranteed and vertical stack areas (Figure 3e) would be obtained. In such case our only constraint in establishing the sets is that the resulting stacks each have height $H_S \leq H^*$ and length $L_S \leq L_{S,\max}$, where $H^* =$ 'current' maximum stack height $\leq H_{S,\max}$ (Figure 4).

There are many ways in which $\mathbf{S}^*$ can be divided into stacks while meeting the maximum height and length criteria. In order to minimize the quantity of stacks, however, a simple greedy approach can be used. Panels are taken from $\mathbf{S}^*$, one at a time and in order. The first panel starts the top layer of the first stack. An attempt is made to add each successive panel to the same layer of the same stack. Whenever this results in $L_S > L_{S,\max}$, a new layer (below the current one) is started. The height of each layer is that of the thickest panel in that layer. Whenever starting a new layer would result in $H_S > H^*$, a new stack is started. This procedure continued until all panels from $\mathbf{S}^*$ have been assigned: the result is M stacks, with stack k having panel set $\mathbf{P}_k$ and $\mathbf{P}_1 \cup \mathbf{P}_2 \cup \dots \cup \mathbf{P}_M = \mathbf{P}^*$, where $\mathbf{P}^* =$ set of all panels in $\mathbf{S}^*$.

Assigning panels to stacks in this manner for the example problem results in $M = 3$ stacks, with $\mathbf{P}_1 = \{8, 12, 13, 14, 15, 1, 19, (17, 35), (22, 23), 2, 3\}$, $\mathbf{P}_2 = \{9, 18, 16, 20, (21, 24), 26, 4, 25, 10, 27, 28, 11\}$, and $\mathbf{P}_3 = \{6, 7, (34, 32), 29, (5, 30), (31, 33)\}$.

Stage 4: Construction Sequence, Panels in Each Stack

As previously mentioned, the stacks formed in Stage 3 both guarantee connectivity and result in vertical stack areas when the panels are taken in the order provided. At this point, however, the build pattern for each stack is top-to-bottom, while left-to-right is preferred. Thus, the construction sequence for the panels in each stack is recalculated, assuming a left-to-right build pattern. The procedure is essentially the same as that used for the entire structure (Stage 2), except that a left-to-right build pattern is used for step 5. Applying the procedure to the example problem results in $S_1 = (8, 12, 13, 14, 15, 19, 35, 17, 22, 1, 23, 2, 3)$, $S_2 = (9, 10, 11, 18, 27, 16, 20, 24, 26, 4, 28, 25, 21)$, and $S_3 = (6, 7, 34, 33, 32, 29, 30, 31, 5)$.

Stage 5: Stack Arrangements

The procedure for forming stacks is similar to that used in panel assignment (Stage 3). For each stack k , panels are taken from S_k , one at a time and in order. The first panel starts the top layer of the stack k . An attempt is made to add each successive panel to the same layer of the stack. Whenever $L_{S,max}$ is exceeded, a new layer (below the current one) is started. This procedure continued until all panels from S_k have been assigned. Note that as the set of panels forming the stack is fixed, $H_{S,max}$ can be exceeded. In this case, iteration is employed to reduce the quantity of panels in each stack until all stacks are of acceptable height (Figure 4).

Assigning panels to stacks in the above manner for the example problem results in $P_1 = \{8, 12, 13, 14, 15, (19, 35), 17, 22, 1, 23, 2, 3\}$, $P_2 = \{9, 10, 11, 18, 27, 16, (20, 24), 26, 4, (28, 25), 21\}$, and $P_3 = \{6, 7, (34, 33), 32, 29, (30, 31), 5\}$. Stack heights are 62, 52, and 34 in., respectively. The first stack now exceeds $H_{S,max}$, so we must iterate as shown in Figure 4 (a single iteration only is used here for brevity):

- Stage 3 is repeated using $H^* = 56$ in., giving $P_1 = \{8, 12, 13, 14, 15, 1, 19, (17, 35), (22, 23), 2\}$, $P_2 = \{3, 9, 18, 16, 20, (21, 24), 26, 4, 25, 10, 27, 28\}$, and $P_3 = \{11, 6, 7, (34, 32), 29, (5, 30), (31, 33)\}$.
- Stage 4 is then repeated, giving $S_1 = (8, 12, 13, 14, 15, 19, 35, 17, 22, 1, 23, 2)$, $S_2 = (3, 9, 10, 18, 27, 16, 20, 24, 26, 4, 28, 25, 21)$, and $S_3 = (11, 6, 7, 34, 33, 32, 29, 30, 31, 5)$.
- Finally, Stage 5 is repeated, giving $P_1 = \{8, 12, 13, 14, 15, (19, 35), 17, 22, 1, 23, 2\}$, $P_2 = \{3, 9, 10, 18, 27, 16, (20, 24), 26, 4, (28, 25), 21\}$, and $P_3 = \{11, 6, 7, (34, 33), 32, 29, (30, 31), 5\}$: stack heights are 56, 52 and 40 in. All stacks are now within $H_{S,max}$, so this solution is acceptable.

Stage 6: Stack Drop-Off Locations

As previously described, all stacks are dropped off along the same edge of the structure and cannot overlap the structure edges. Furthermore, all stacks have one length edge flush with the dropping edge. This results in a single area for each stack, within which that stack must be completely contained. If we then assume a discrete x-direction step size (say, 1 inch), a finite set of drop-off locations for each stack can be calculated. The optimal location for a stack (for the given step size) can then easily be found by simply examining all drop-off locations and selecting the one which minimizes the weighted panel move distance. Figure 8 shows the

overall solution for the example problem (panels each stack, panel sequence, and stack drop-off locations).

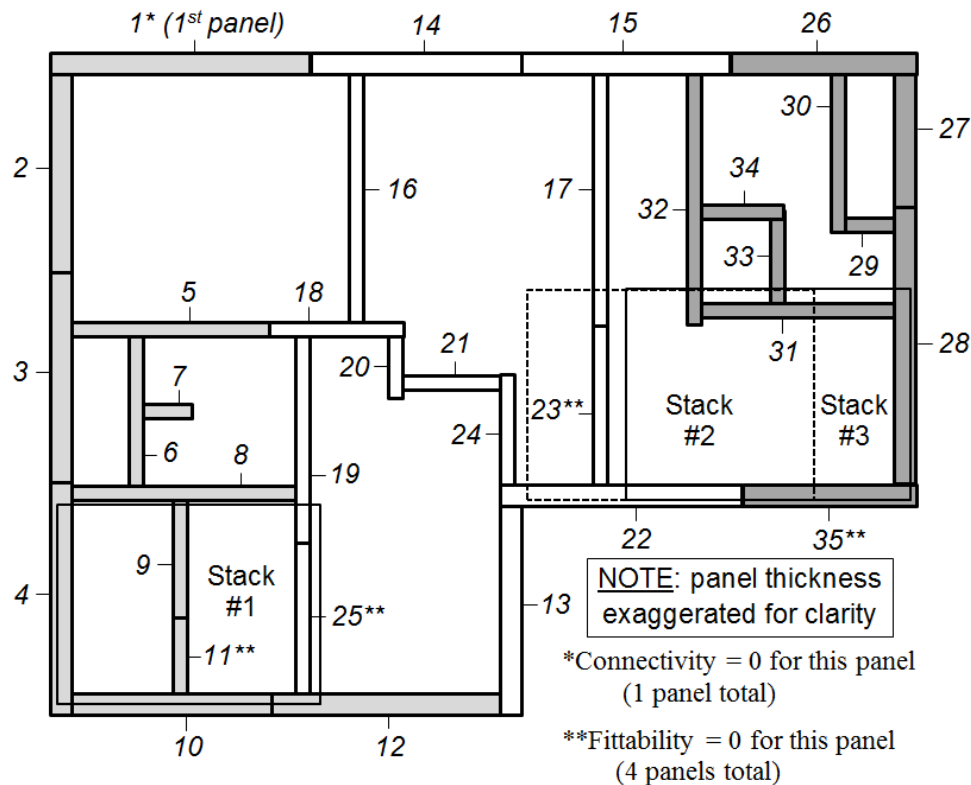


Figure 8. Overall solution, example problem.

COMPUTATIONAL EXPERIMENTS

Experimental Design

A set of computational experiments were conducted to establish the performance of the proposed approach to panel stacking, panel sequencing, and stack locating in panelized residential construction. Three sizes of residential single-story home designs were investigated – small (< 1500 ft²), medium (1500-3000 ft²), and large (>3000 ft²). For each scenario, five home plans were randomly chosen from an online database of housing plans (The Home Plan Group, 2009), giving fifteen problems. For each problem, the structure was panelized using a preferred panel length of 10 ft. (8-12 ft. is common in practice). Panel lengths were adjusted as required to account for door and window openings, with a maximum panel length of 12 ft. observed. All fifteen panelization plans can be found in Appendix D of Guo (2010). Maximum stack height and stack length were 60 in. (5 ft.) and 150 in. (12-1/2 ft.) respectively: these are typical values found in practice.

For each problem, the stacks, construction sequence and stack locations were found using three different approaches: manual solution, commercial software, and the proposed algorithm. A professional panel designer, with eight years of experience generating panel stacks for residential construction, provided manual solutions for all problems. Solutions were also generated with a widely-used, commercially-available wall panel design and stacking software package. For both the manual and commercial software approaches, the standard practice of separate exterior and interior panel stacks was employed: the resulting stacks for all problems can be found in Appendix D of Guo (2010). Our field observations over many structures, and discussions with panel manufacturers, indicate that the methods used by the panel designer and commercial software are representative of those used throughout the industry today.

In both the manual and commercial software approaches, the only result generated is the set of stacks. Neither the actual sequence in which the panels in each stack are to be used, nor the stack drop-off locations, are provided. Regarding the panel sequence, we assume that the panels in each stack are used in stack order, as they are with the proposed algorithm. For multi-panel stack layers, we determine the best possible sequence for the panels as follows. The order in which the panels are presented, left-to-right in the stack, is taken as the initial sequence. This is checked and adjusted as necessary to obtain maximum connectivity. If no adjustment is needed, it is checked and adjusted to obtain maximum fittability. When workers in the field use panels in stack order, the results thus show directly the problems they would encounter with connectivity and fittability. When workers do not take panels in the order provided (but instead move panels off to the side, onto the floor, etc., to get a panel which 'worker better,' i.e., has better connectivity and/or flexibility) the results can be taken as an indicator of the amount of work they need to do in moving such panels. We must keep in mind, however, that in such case the workers will not likely know the best selections to make and as such may move a lot of panels and still encounter connectivity/fittability problems. Thus, the results likely overestimate the true connectivity/fittability in such cases. For determining stack drop-off locations in the manual and computerized approaches, we use the same optimal procedure employed in the proposed approach (Step 6).

The proposed algorithm was coded-up in C++ using Visual Studio 2010, and run on a 2.8GHz laptop. To aid in program debugging and verification, a separate program for drawing the panelization plan, then drawing the stacks at their drop-off locations and animating the sequence in which the panels from each stack are placed, was developed using C++ and PROOF3D animation software (Wolverine Software Corp.).

Results

Experimental results are presented in Tables 1 and 2. For each case and solution approach, the four performance measures (M , WMH , $CONN$, and FIT) are presented. An additional measure, total panel material handling distance, MH , is also provided to get a feel for the actual distances traveled by workers. Table 1 shows the actual values for the performance measures,

while Table 2 shows the percentage improvement in each measure using the proposed approach. To aid in understanding the results, the panel stacking and sequencing solutions for case M-4 are shown in Figures 9 (manual approach) and 10 (proposed approach). These figures also indicate panels for which connectivity or fittability was not achieved.

Table 1. Computational results for proposed algorithm vs. existing approaches.

Case	N	Panel Designer					Commercial Software					Proposed Algorithm				
		M	MH, ft.	WMH, ft. ²	CONN	FIT	M	MH, ft.	WMH, ft. ²	CONN	FIT	M	MH, ft.	WMH, ft. ²	CONN	FIT
S-1	23	3	472	3,524	86%	82%	3	447	3,527	77%	64%	2	384	3,038	100%	100%
S-2	23	3	337	2,655	77%	76%	3	389	3,024	82%	71%	2	327	2,554	100%	100%
S-3	27	3	421	3,230	85%	88%	3	473	3,525	85%	88%	2	415	3,107	100%	100%
S-4	25	3	484	3,748	88%	83%	3	520	4,107	88%	79%	2	419	3,368	100%	100%
S-5	33	4	619	4,576	78%	78%	4	644	4,827	88%	84%	3	563	4,058	100%	100%
M-1	46	5	1,391	10,977	82%	84%	5	1,347	10,681	87%	80%	4	1,296	10,305	100%	100%
M-2	51	6	1,447	11,515	90%	82%	5	1,476	11,514	90%	90%	4	1,266	10,073	100%	100%
M-3	49	6	1,245	9,498	83%	83%	4	1,260	9,629	90%	79%	4	1,272	9,371	100%	100%
M-4	64	8	1,572	13,355	81%	74%	6	1,654	14,154	86%	81%	5	1,354	11,494	100%	100%
M-5	59	7	1,381	11,155	86%	79%	5	1,585	12,670	88%	85%	5	1,425	11,403	100%	100%
L-1	90	11	3,549	29,293	81%	80%	8	3,618	29,930	81%	81%	7	3,200	26,822	100%	99%
L-2	91	10	3,244	28,613	84%	80%	8	3,599	31,819	83%	80%	7	2,910	25,487	100%	100%
L-3	93	11	2,996	26,195	79%	81%	8	3,343	29,468	89%	81%	8	2,792	24,350	100%	100%
L-4	87	10	3,170	27,572	83%	79%	8	3,641	31,475	81%	84%	7	2,511	22,106	100%	100%
L-5	84	10	3,691	33,479	78%	77%	8	3,731	33,621	87%	82%	7	3,496	31,669	100%	100%

Table 2. Percentage improvement obtained using proposed approach vs. existing approaches.

Case	<i>N</i>	Improvement over Panel Designer					Improvement over Commercial Software				
		<i>M</i>	<i>MH</i>	<i>WMH</i>	<i>CONN</i>	<i>FIT</i>	<i>M</i>	<i>MH</i>	<i>WMH</i>	<i>CONN</i>	<i>FIT</i>
S-1	23	33%	19%	14%	16%	22%	33%	14%	14%	30%	56%
S-2	23	33%	3%	4%	30%	32%	33%	16%	16%	22%	41%
S-3	27	33%	1%	4%	18%	14%	33%	12%	12%	18%	14%
S-4	25	33%	13%	10%	14%	20%	33%	19%	18%	14%	27%
S-5	33	25%	9%	11%	28%	28%	25%	13%	16%	14%	19%
M-1	46	20%	7%	6%	22%	19%	20%	4%	4%	15%	25%
M-2	51	33%	13%	13%	11%	22%	20%	14%	13%	11%	11%
M-3	49	33%	-2%	1%	20%	20%	0%	-1%	3%	11%	27%
M-4	64	38%	14%	14%	23%	35%	17%	18%	19%	16%	23%
M-5	59	29%	-3%	-2%	16%	27%	0%	10%	10%	14%	18%
L-1	90	36%	10%	8%	23%	24%	13%	12%	10%	23%	22%
L-2	91	30%	10%	11%	19%	25%	13%	19%	20%	20%	25%
L-3	93	27%	7%	7%	27%	23%	0%	16%	17%	12%	23%
L-4	87	30%	21%	20%	20%	27%	13%	31%	30%	23%	19%
L-5	84	30%	5%	5%	28%	30%	13%	6%	6%	15%	22%

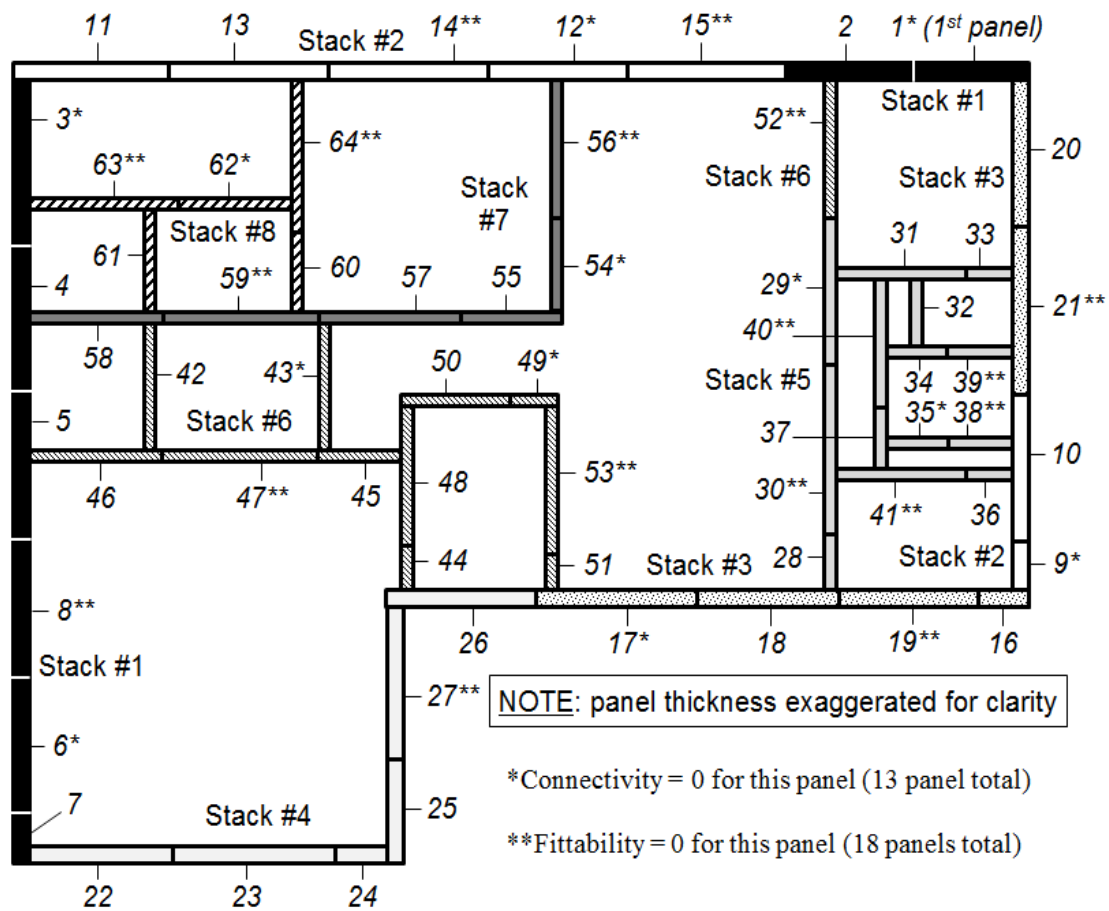


Figure 9. Case M-4 (64 panels), as solved by the panel designer.

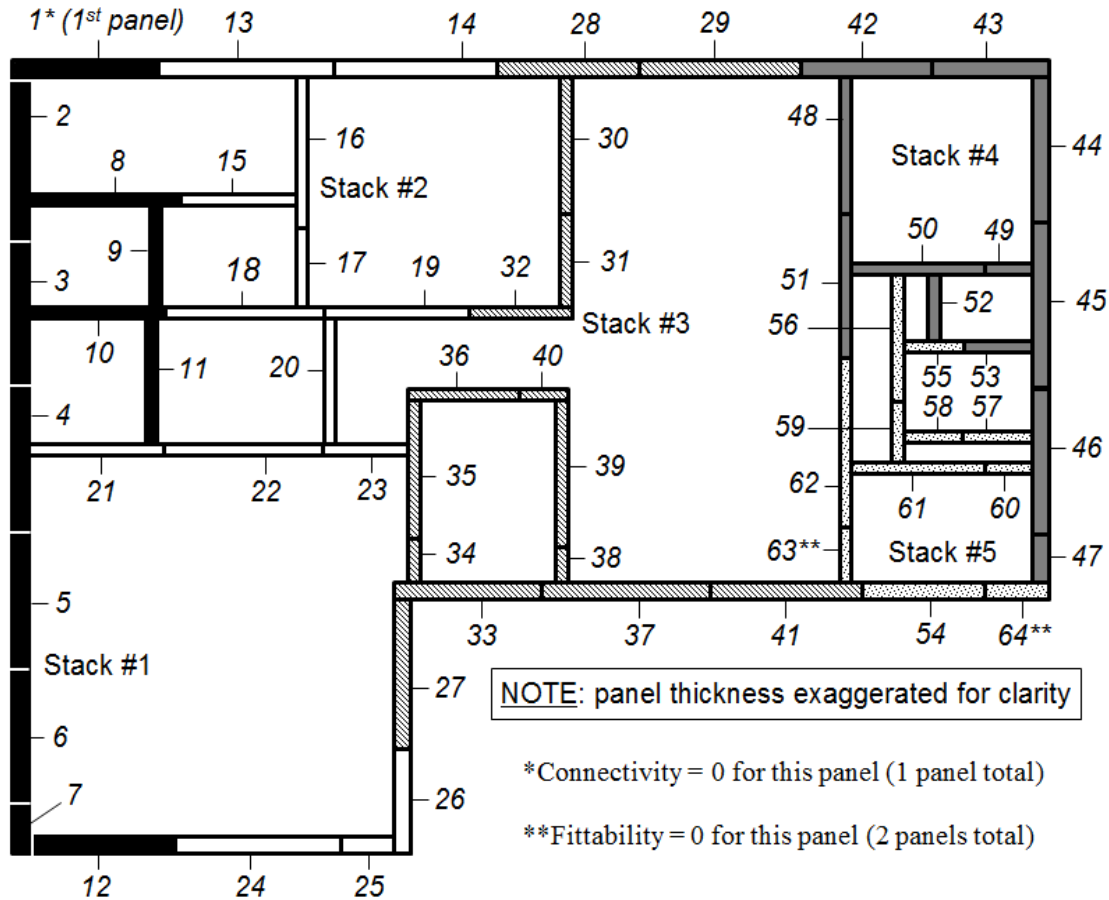


Figure 10. Case M-4 (64 panels), as solved by the proposed algorithm.

Performance of the proposed algorithm, as compared to both existing approaches, is as follows:

- The quantity of stacks (M) was reduced in all cases compared to the manual approach, and in twelve of fifteen as compared to the commercial software approach. In no cases did the proposed approach result in a greater quantity of stacks.
- Total panel material handling distance (MH), as compared to the manual approach, decreased for thirteen of the fifteen cases. The improvement ranged from 1-21% (average = 8%); for the two non-improving cases (M3 and M5), the proposed approach was worse by only 2% and 3%, respectively. Compared to the commercial software approach, total panel move distance decreased for fourteen of the fifteen cases, with the improvement ranging from 4-31% (average = 14%) and performance worse by only 1% for the sole non-improving case (M-3). In terms of actual values, the improvement of 31% for case L-4 represents a reduction in material handling distance of 659 feet: the workers are carrying panels for about 1/8 mile less using the proposed approach.
- Total weighted panel material handling distance (WMH), as compared to the manual approach, decreased for all cases but one with improvement ranging from 1-20%. The

sole non-improving case (M5) exhibited a performance decrease of 2%. Compared to the commercial software approach, *WMH* decreased in every case, with the improvement ranging from 3-30%. The average improvement over the manual and commercial software approaches was 8% and 14%, respectively, the same values found for *MH*.

- Connectivity (*CONN*) was improved in all cases. While the proposed approach guarantees 100% connectivity, the manual approach provided at most 90% connectivity (M-2) and an average value of 83%. The commercial software approach was very similar, with a maximum of 90% connectivity (M-2, M-3) and an average of 85%. The percentage improvement in connectivity using the proposed approach ranged from 11-30% over all cases, with an average 21% improvement over the manual approach and 17% over the commercial software approach. Considering case M-4, the manual approach results in thirteen panels having zero connectivity (Figure 9): each of these panels is free-standing and requires substantial bracing upon installation. With the proposed approach (Figure 10), only the first panel has zero connectivity (recall this cannot be avoided).
- Fittability (*FIT*) was improved in all cases. Both the manual and commercial software approaches had an average fittability of about 80%: the maximum value observed was 90% (M-2). Fittability with the proposed approach was 100% in all cases except L-1, where it was 99%. This provided improvement ranging from 11-56% over all cases, with an average 25% improvement over both the manual and commercial software approaches. Again considering case M-4, the manual approach results in eighteen panels having zero fittability: each of these panels must be squeezed into place between already-completed panels. The proposed approach (Figure 10) results in only two panels having zero fittability, both of which are unavoidable.

In terms of solution speed, the algorithm solved each problem in less than one second.

Discussion of Results

The computational results indicate that the proposed approach to panel stacking, panel sequencing, and stack locating appears to be a significant improvement over existing methods. The proposed algorithm dominated both the manual and commercial software approaches for thirteen of the fifteen cases: *M*, *MH*, *WMH*, *CONN*, and *FIT* were all improved upon. In the remaining two cases (M-3, M-5), only *MH* and/or *WMH* were worse, and then just slightly (1-3%). Considering all cases and both existing methods, we find that on average the proposed approach results in

- 25% fewer stacks to deliver.
- an 11% reduction in the total distance (and weighted total distance) the workers need to walk while carrying panels.

- the elimination of all unavoidable free-standing panels, and thus the additional work required to brace such panels. This represents a 20% reduction in such panels encountered using existing methods.
- the elimination of all unavoidable squeeze fits except one (in case L-1), and thus the additional work (and aggravation) required to position such panels. This represents a 25% reduction in such panels encountered using existing methods.

While the magnitude of reduction in *MH* and *WMH* may not seem too impressive in isolation, it becomes more significant when the quantity of stacks is considered. In general, as *M* increases, *MH* (*WMH*) decreases: in the limit, each panel has its own stack and there is no *x*-distance move component at all. Conversely, as *M* decreases, we would expect *MH* (*WMH*) to increase. The proposed algorithm dramatically decreases *M*, but in spite of this *MH* (*WMH*) decreases as well. The decrease in *M* can be partially explained by the fact that with both existing approaches, each stack can consist of either exterior or interior panels only: this can result in spare capacity in the last external stack which cannot be used. But this does not account for the entire decrease in *M*: the proposed algorithm itself comes into play and avoids trading-off material handling distance for stack quantity as would be expected.

The 20% and 25% average reduction in *CONN* and *FIT*, respectively, is extremely important. Our field observations, over many structures from several different construction firms, have repeatedly shown us instances of freestanding panels (following the first panel) being erected, as well as workers struggling to force-fit panels which require a squeeze fit (often hammering the panel into place as a last resort). The proposed approach eliminates the first problem and minimizes the second. This will have a substantial impact on how field crews work, as well as the safety and efficiency with which positioning and bracing are performed.

It should also be kept in mind, when comparing performance, that the panel designer and commercial software do not generate full solutions and we have determined the *best possible values* for the missing items. Our field observations and discussions with panel manufacturers and construction crews, however, indicate that the best values are seldom realized in practice. Thus, we have likely overestimated performance of the current methods by a substantial margin.

CONCLUSIONS

In this paper, an approach and algorithm for solving the panel stacking, panel sequencing, and stack locating problems in residential panelized construction were presented. The focus was on maximizing performance: panel interference was ignored, being left for a later stage in the design process. Performance was investigated by experiments comparing the algorithm to solutions generated manually (experienced panel designer) and via commercially-available software for fifteen cases. The results indicate that the proposed approach can improve the process considerably, simultaneously reducing the quantity of stacks, the distance workers must walk carrying panels, the bracing needed to erect panels, and the additional work needed to position panels when 'squeeze fit' scenarios are encountered. Reducing the quantity of stacks

has always been an objective for the panel maker, so as to minimize the quantity of trips to the job site. The goal of this paper was to develop methods for solving the aforementioned problems which also make the job safer and more efficient for the workers. The approach and algorithm presented satisfy this goal, without compromising the original objective of minimizing stack quantity. It should also be noted that the algorithm works with any building shape and always provides feasible solutions, issues encountered with the only other reported algorithm which tackles the problems ignoring panel interference (Guo, 2010).

Several issues, however, remain to be explored. In terms of the algorithm, alternatives need to be explored for Stage 3 (dividing the overall construction sequence into stacks). A simple greedy approach was used in this paper, with each stack filled as much as possible. While this minimizes the quantity of stacks, it can also result in large move distances for some panels. Unless the last stack is full, panels can be distributed amongst the stacks differently (e.g., balance the panels over the stacks) without affecting stack quantity: a different solution may have a lower MH (WMH). In terms of the experiments, the effect of alternative panelization strategies needs to be explored. This paper assumed a single preferred panel length of 10 ft. In practice, we can employ a smaller preferred panel length (each panel smaller, but more of them) or a larger length (each panel bigger, but fewer to worry about). Further improvement in M , MH (WMH) may be possible if the panelization strategy is taken into account for a given structure.

In terms of model validity, two items need to be addressed. First and foremost are the issues of unload interference and stack interference. When either of these occurs, panels must be moved temporarily (something we have been trying hard to avoid along) or drop-off locations must be adjusted, or some combination of the two (or something else) is needed. Methods are needed to cope with both unload and stack interference: efforts are underway to develop a post-processing algorithm which 'adjusts' solutions as required to eliminate interference. The second item to address concerns the underlying assumption of one stack in process at a time. While construction occurs in this manner in many instances, there are other times where multiple stacks are worked on at the same time to speed up the process. In such cases, the panel sequence can no longer be solved for each stack in isolation, as panels from different stacks can intermix during construction. Additional work is needed to tackle this difficult problem.

Finally, we note that the proposed algorithm solves for what panels go into each layer of each stack (and the sequence they are to be taken in), but not the panel *location* in each layer. Both performance and validity could be improved by determining such locations: MH and WMH would then be based upon the actual panel locations in the stack, rather than stack centroids. In similar manner, we know that either the top or bottom plate is flush with the dropping edge for each stack: a more sophisticated algorithm would calculate this *orientation* of each panel in the stack. This is an important design variable: we have repeatedly seen workers in the field remove panels from stacks and find it necessary to rotate the panels 180° (xy plane) prior to erecting them. As panel orientation does not impact any of the existing performance measures, another suitable measure would need to be developed.

A final issue to be addressed is the potential impact of the proposed approach on the factory, as it requires panels to be stacked differently (exterior and interior panels in the same stack, different panel thicknesses allowed in the same layer). Preliminary discussions with panel manufacturers have indicated that this is not expected to cause any major difficulties. In fact, this change to the way stacks are made is actually desirable: it will allow the factory to move towards *lean panel production*, making them just-in-time for each stack as opposed to batching (all exterior stacks, then all interior stacks). It will also allow for a single, standardized set of methods, tools, etc., for stacking, stack packaging, transport, etc., as only one 'kind' of stack is then used as opposed to exterior stacks (few panels, each big and heavy, few layers) and interior stacks (many panels, each relatively light, many layers). Thus, the proposed approach not only brings lean to the construction site, it moves it upstream to the panel manufacturer as well.

NOTATION

Input variables:

N	=	quantity of panels
L_i	=	length of panel i (see Figure 2).
t_i	=	thickness of panel i (see Figure 2).
b_i	=	1, panel i is an exterior panel; 0 o/w (interior)
d_i	=	1, panel i oriented vertically; 0 o/w (horizontal)
$conn_i$	=	set of panels connecting with panel i
$conn_{iR}$	=	set of panels which connect with panel i via panel's right edge
(x_i, y_i)	=	(x, y) coordinates of panel i (centroid) in the panelization plan
$yedge_i$	=	y -coordinate of panel i 's top edge, panelization plan
$H_{S, \max}$	=	maximum stack height
$L_{S, \max}$	=	maximum stack length

Output variables:

M	=	quantity of stacks
P_k	=	set of panels comprising stack k and their arrangement into layers
	=	$\{(\text{panels in top layer}), (\text{panels in 2}^{\text{nd}} \text{ layer}), \dots, (\text{panels in bottom layer})\}$
S_k	=	construction sequence, panels in stack k
(u_k, v_k)	=	(x, y) coordinates of stack k 's drop-off location (centroid) , panelization plan.

Working variables:

IP	=	set of panel precedence constraints = $\{(i, j) \mid \text{panel } i \text{ must precede panel } j\}$
S^*	=	overall panel construction sequence (all panels)
FP	=	first exterior panel in overall panel construction sequence
LP	=	last exterior panel in overall panel construction sequence

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4.2. Simulation modeling and ergonomic assessment in panelized construction

Shewchuk JP, Nussbaum MA, Kim S, Sarkar S: Simulation modeling and ergonomic assessment of complex, multi-workers physical processes. Submitted to the IEEE Transactions on Human Machine Systems.

Abstract

Discrete simulation of complex, multi-worker physical processes, for the purpose of ergonomic and/or performance analysis, is still relatively undeveloped. Existing approaches typically have taken either a classical simulation view of the problem (focus on activities, resources, and queues: workers treated as simply another machine) or an analytical ergonomics perspective (detailed human modeling and ergonomic assessment for well-defined, limited tasks). This paper presents a new way to tackle such problems, based upon elements of both of these approaches. Novel methods are described for modeling complex, multi-worker physical processes within a traditional discrete-event simulation environment. These methods result in a high-level language for generating activity-based process models quickly and easily, based upon simplified activity representations. Laboratory experiments are then used to derive equations which can then be used to generate ergonomic assessments (i.e., relative injury risks) for the most influential activities. By implementing these equations using data generated from a simulation run, estimates of ergonomic consequences can be obtained. To illustrate the approach, it is applied to the panelized residential housing construction process, where multiple workers build houses by moving and installing large, heavy prefabricated wall panels. The example illustrates the steps presented and feasibility of the approach.

I. INTRODUCTION

Many systems employ complex, manual physical processing, where items must be moved and manipulated by multiple workers. Of considerable concern in such systems is the extent to which workers are exposed to substantial physical demands and the associated level of musculoskeletal injury risks. To ensure that the risks to each worker are acceptable, the process must be carefully designed. Additionally, it is usually important to be able to determine how well the system performs with respect to some common metric such as throughput or cycle time.

Because of the complex interactions between workers and level of detail required, simulation is the only viable alternative for modeling and analyzing such systems [1]. Two broad approaches exist for incorporating humans in simulations.

- 1) *Process-oriented simulation*: Simulations based on traditional modeling concepts and methods (activities, resources, queues, etc.). Workers are typically treated as machines: human activities are difficult to model and ergonomic measures difficult to establish.

- 2) *2)Human-focused simulations*: Simulations where humans are modeled in detail (anthropometric data) and advanced tools used to estimate ergonomic exposures/risks for well-defined activities (e.g., lift task). Not well-suited to complex systems where a great variety of tasks are possible and/or multiple workers can be performing multiple tasks simultaneously.

In this paper, we propose an alternative approach to simulation modeling and ergonomic assessment of complex, multi-worker physical processes. The idea is essentially to combine elements of both current approaches: develop discrete simulation models and methods which represent complex human tasks and interactions with sufficient validity, then use advanced methods to assess ergonomic exposure/risk based upon activity data generated during simulation.

To help explain and demonstrate the approach, it is applied to the panelized residential construction process (Fig. 1). This is a form of building construction where houses are built from prefabricated walls (panels) made in a factory, rather than 'stick-built' on-site from piles of lumber. Once manufactured, the panels are arranged into stacks and the stacks trucked to the job site and dropped off on the structure sub-floor. The construction process consists of each panel being unloaded from its stack, moved, and erected at its final location/orientation in the structure. The panels can be very large (2.44 m high x 4.88 m long) and heavy (over 113 kg): processing is typically entirely manual, using between 1-4 workers each panel. Because the workers spend the majority of their time moving, manipulating, and/or installing the panels, physical demands and injury risks are substantial [2][3]. Efforts are underway to develop methods which plan panels, stacks, stack deliveries, and construction planning techniques to minimize this ergonomic risk [4][5]: discrete simulation and ergonomic analysis are essential to these efforts.

Simulation modeling and ergonomic assessment of the panelized residential construction process is difficult, however, as there are no set components or systems: a standard panel size does not exist and houses can take any size, shape, and form. This results in an almost limitless variety of possible panels to move and move objectives (i.e., panel's final location/orientation with respect to its starting stack location/orientation). Thus, the set of construction activities needed to cover all possibilities is extremely large. Additionally, there are many different ways to perform a given construction activity (exactly where workers stand, specific detailed motions used may vary from one worker to another, etc.), and many different parameters (panel size and weight, whether panel sheathing used, site conditions, etc.) to be considered. Overall, panelized residential construction is considered to be an excellent test bed for the proposed approach to simulation modeling and ergonomic assessment of complex, multi-worker physical processes.

II. LITERATURE REVIEW

Process-oriented discrete simulation has been widely used over the years for detecting various sources of risk during system design. The use of such models can eliminate the need for

physical scale models during the initial design stage even for complex products, such as aircraft [6]. For systems incorporating humans, however, adequate attention is not paid in modeling human behavior [7]. The literature on process-oriented simulations involving humans can be broadly categorized into the following:

- 1) *Those that consider humans as machines:* The focus of such simulations is not humans, but workstations and/or processes [8]. Some early effort on modeling worker behavior in a manufacturing environment using commercial software was made by [9]. They modeled group work behavior for throughput analysis by changing mode of operations or worker qualifications. As humans are modelled as machines, ergonomic issues are never considered in these studies.
- 2) *Those that consider humans in more detail:* The objective of these simulation models is modeling human behavior, without considering the details of the tasks/physical activities that each individual is performing. Reference [10] differentiated worker-integrated simulations from worker-oriented simulations: the logistic system is evaluated in the former, and the factors influencing the workers are analyzed in the latter. They discussed an approach for worker-oriented simulation by considering specification of individual workers in the simulation model. Reference [11] discussed a simulation approach to incorporate varying worker activity times in the context of a manufacturing system design. For developing complex simulation of human interactions, researchers often use autonomous agent-based models (e.g., [12]) attributes used for individual agents can be work experience, qualification, competence level, etc. None of these studies consider ergonomic issues, however.
- 3) *Those that look at detailed ergonomic modeling:* The purpose of such models is evaluation and prediction of human factors in work processes. Reference [13], for example, presented a geometric inverse kinematic algorithm to predict reach postures. In their study, the arm is modelled as a four-degrees-of-freedom kinematic linkage system. The effects of fatigue and rotation schedules on unmanned vehicle control performance are examined using simulation in [14]. Reference [15] showed an ergonomic simulation model of the factory workers considering the human body structure, work motions, and work semantics. An ergonomic performance evaluation of an automobile disassembly system using simulation was presented in [16]. In this study, the following distinct activity categories were considered: (1) direct value-adding activities, (2) material handling, (3) casual (cleaning the workplace, etc.), (4) unplanned breaks, and (5) transport. Reference [17] discussed several commercial products available for conducting ergonomic analysis using simulation. More recently, [18] provided a discrete event simulation approach for comparing ergonomic impacts (fatigue prediction) of alternative assembly line designs. In these and related studies, simulation is typically performed at the workstation level, with the focus on human-machine interaction rather than interactions among multiple workers. Additionally, they consider well-structured, controlled work environments where activity variations are limited.

Overall, the use of discrete simulation as a proactive ergonomic tool has been limited to relatively controlled work environments. Managers in charge of system design are still skeptical whether simulation modeling of human behavior is even feasible [6].

In occupational ergonomic studies, human-focused simulation plays a vital role. These studies on human activities often aim to investigate how the neuromuscular and musculoskeletal systems coordinate to produce movement [19]. In such cases, system analysis is typically done by collecting data from human subjects (i.e., workers) through direct observation, measurement, questionnaires, or interviews. However, all of these studies focus on workstation-level assessment without considering the overall system-level impact of the workers [18]. Focusing only on the workstation-level eliminates the need to model interaction/ coordination of multiple workers, which are more complex in nature than modeling individual workers. Digital human modeling, the computerized representation of human body and its interaction with the environment [20], is also available. In this approach, an anthropometric database and posture/motion prediction algorithms are used to simulate work tasks in virtual environments. Several commercial digital human modeling software tools are available: these include D Static Strength Prediction ProgramTM (3DSSPP) [21], JACK (Siemens Product Lifecycle Management Software, Inc.), SantosHumanTM (SantosHuman Inc.), and Delmia (Dassault Systems, Inc.). Reference [22] presented a novel approach to human motion simulation where real human motion samples are stored in a database, retrieved during simulation, and then modified as necessary to match the actual scenario as closely as possible. This work is perhaps the closest to the proposed research in terms of the goal of linking simulated processes and actual ergonomic data, but again focuses on individual workers and tasks. Overall, digital human modeling is a promising tool for proactive ergonomic analysis, but the validity of posture/motion prediction is often limited to relatively simple movement circumstances [23] and the approach is not aimed at multiple humans working together.

Finally, the literature shows a gap in the research on simulation of collaborative performances and teamwork processes [24], which is addressed in this research. Task network modeling (task analysis) is a viable approach for modeling human behaviors in simulation [25]. In this approach, the function performed by an individual is decomposed into several sub-functions. Each sub-function consists of several tasks. These tasks are then modeled independently into the simulation. This approach is used in [26] to simulate foot behaviors during manual material handling tasks. Data from their laboratory study indicated that only four specific behaviors accounted for over 90% of the observed foot behaviors. Categorizing behavior in this manner helps to reduce the complexity of the simulation. No previous studies, to our knowledge, have considered task analysis for simulation modeling of multiple worker coordination. In the following sections, we describe in detail how we extended the task analysis approach to model complex physical activities that require multiple workers to participate.

III. MODELING FRAMEWORK AND APPROACH

A *physical process* is taken to mean a sequence of manual activities required to move/manipulate a particular item (or batch of items acting as one) from one location/orientation to another. We are concerned here with gross physical movements (i.e., material handling) only, not fine detailed movements (e.g., manual assembly). One or more workers (humans) are required to perform the physical process: the workers are seized at the start of the process and released at the process' end (if an individual is needed for only a portion of the process, the process is sub-divided so the rule still applies). Workers are modeled in low fidelity and as rigid bodies: we are interested in the movement and location/orientation of workers in two-dimensional space (xy plane) only. Note that this does not mean ergonomic aspects related to

postures, motions, joint loads, etc. are not considered, but rather only that this level of detail is not modeled directly in the simulation. The mechanisms by which these issues are incorporated are explained shortly.

The overall approach to simulation modeling and ergonomic assessment of multi-worker physical processes is as follows. Basic processes are first identified, and representative sets of activities which can be used for each are developed. Each activity utilizes low-fidelity modeling: the actual activity is not only simplified but also approximated as required in order to obtain a task-based representation that is highly tractable (from both modeling and coding perspectives). Video analysis, laboratory experiments, and field studies are then used to establish activity time and/or rate distributions, which can then be used to generate valid time estimates for activity execution. Extensive laboratory experiments are performed to obtain diverse data for various activities, which in turn is used to derive equations (i.e., prediction tools) for ergonomic assessment. Note that such equations are required, since only a finite number of activities/situations can be simulated in a laboratory versus the much broader set that can occur in the field. A few prediction tools exist, such as different types of regression models (e.g., [27],[28]); however, the focus of these is on a single worker lifting under typically limited or controlled circumstances. During simulation, relevant item and worker location/orientation and move data are stored for each activity. Following simulation, this information is used along with the aforementioned ergonomic equations to facilitate ergonomic assessment at the worker level for the given scenario simulated.

IV. SIMULATION MODELING METHODOLOGY

A. Identify Processing Approaches and Major Processes

The first step in simulation modeling of complex, multi-worker physical processes is to observe the process at a high level in order to get an overall idea of what is occurring, specifically what kinds of items are being moved, what the objectives are, process boundaries, and the extent to and general ways in which workers are involved. At this level, one can usually distinguish between different overall approaches used for satisfying the physical processing objectives: we refer to these as processing approaches. Additionally, one often finds similar steps being taken, albeit at different time and/or under different conditions, across different approaches. These major processes in effect become the basic 'blocks' used to define the different processing approaches employed. The goal of the first step is then to establish the different processing approaches employed and identify the major processes involved.

B. Panelized residential construction example: Fig. 2 illustrates the basic terminology used when discussing the panelized residential construction process. Two processing approaches were identified:

- 1) *Direct Panel Install:* The panel is unloaded from its stack, then carried to a point near its final location in the structure and tipped upright. It is then installed (moved and manipulated into its final location/orientation), then fixed (permanently attached to other

connecting panels at that location) and braced (temporary bracing applied, as needed, to ensure panel remains stationary and rigid)..

- 2) *Indirect Panel Install*: The panel is unloaded its stack, then carried to an area where it can be stored temporarily by leaning the upright panel against a finished wall. When processing is ready to resume, the panel is retrieved from that location, carried to the install location, then installed, fixed and braced as before.

Based upon the above, six major processes can be identified: UNLOAD, CARRY, STORE, RETRIEVE, INSTALL, and FIX/BRACE. Direct panel install can then be expressed as UNLOAD → CARRY → INSTALL → FIX/BRACE; indirect panel install as UNLOAD → CARRY → STORE → RETRIEVE → CARRY → INSTALL → FIX/BRACE.

B. Identify processing alternatives, define activity classes

There can be many different ways for workers to implement a given processing approach. For example, a worker moving an item from A to B may choose to carry the item in front of their body, at their side, or over their shoulder. Furthermore, there may be a need to pick up and put down the object in a different way in each case. Each different way to implement a processing approach is referred to as a processing alternative. Because processing alternatives differ, yet each still consists of the same major processes, we must then have alternative ways to perform each major process. Each of these is referred to as an activity class.

To establish processing alternatives and activity classes for a given processing approach, it is necessary to observe the processing approach in action for various items, conditions, etc., and determine how workers implement the approach. This will simultaneously result in processing alternatives and activity classes. It is also important at this step to try to establish the conditions under which each processing alternative is used: this information can be used at a later stage for processing validation and/or in studying how the process is planned (decision-making).

Panelized residential construction example: A total of 39 top-level activity classes (7 UNLOAD, 28 CARRY, one each for STORE, RETRIEVE, INSTALL, and FIX/BRACE) were identified for both direct and indirect panel install: these are defined in Table 1. Representative illustrations (simulation animations) of several activity classes are shown in Fig. 3. The overall processing alternatives for direct panel install are shown in Fig. 4. Eight alternatives were identified for single-worker panel processing, whereas three alternatives were found when multiple workers were employed. These processing alternatives were identified via rigorous analysis of video recordings of the panelized residential construction process over multiple houses and by multiple contractors. Overall processing alternatives for indirect panel install are highly similar (the only major difference being the addition of STORE and RETRIEVE), and thus these are not further discussed.

C. Model Activity Classes

Activity classes can be modeled in different ways, depending upon the nature of the activities they represent. Simple activities, for example, are often straightforward to model via a sequence of tasks. This may be difficult for complex activities, however: alternative methods may be required. Additionally, it is helpful to know the relationship between workers and the item during activity execution, as activity classes having similar relationships can be modeled (and thus coded) similarly. Based upon these ideas, seven different kinds of activity classes are recognized as follows:

- 1) *Attached Moving Workers Simple Activity Classes* The item undergoes a simple continuous motion (translation and/or rotation), definable via a single task. Workers move with the item, but do not change location/orientation with respect to the item - the workers act as if 'attached' to the item. A move rate is associated with the activity class: activity duration is then calculated based upon the move rate and the absolute magnitude of the move performed. Example: one or more workers carrying an item, in front of them, as they move it from point A to B.
- 2) *Unattached Moving Workers Simple Activity Classes* The item again undergoes a simple, continuous motion and workers move with the item. Here, however, workers simultaneously change location/orientation with respect to the item. A move rate or duration is associated with the activity class: in the former case activity duration is calculated as before. Example: two workers pushing an item into place between two other items: as they move the item, they must change position with respect to the item in order to be out of the way.
- 3) *Stationary Workers Simple Activity Classes* The item once more undergoes a simple, continuous motion, but now worker remain stationary (no change in location or orientation). These activity classes cover small moves performed to reposition or reorient an item at a particular location. Movements are typically too small to get valid activity time estimates via activity rates and move distances: activity durations are thus necessary. Example: workers, holding an item off the ground, lower that item to the ground.
- 4) *Complex Activity Classes* The item undergoes a complex sequence of motions, defined via a sequence of tasks. Each task: item movement, worker movement, or both simultaneous item and worker movement. For such activities:
 - the activity is modeled in low fidelity (i.e., approximate the activity via some small set of tasks such that the real-world activity is recognizable when the simulated activity is animated).
 - surrogate time/rate data is used for task durations. Any values can be used, as long as they are deemed to be correct proportion to one another (in terms of the low-fidelity activity animation). If, for example, the second task is deemed to take roughly twice as long as the first, the first task can have any time t and the second is then $2t$.
 - activity durations are required. Once activity duration is established, the set of individual task durations are scaled so that they sum up to the complex activity duration.
- 5) *Composite Activity Classes* The item again undergoes a complex sequence of motions, but these are now defined via combinations of other activities. Each combination can consist of either
 - one or more already-defined activity classes. In such case, composite activity duration is calculated directly by summing up the lower-level activity durations.

- one or more new activity classes (indirect activities classes, see below). Composite activity duration must be established directly.
- 6) *Indirect Activity Classes* As noted above, these are activities which can be combined to result in composite activities. They are modeled in a similar manner to complex activity classes (i.e., the activity is modeled in low-fidelity and surrogate time/rate data is used for task durations). Unlike complex activity classes, however, actual activity duration is never calculated for indirect activities (as they are never executed directly). Once composite activity duration is found, the entire set of tasks durations, considering all indirect activities comprising the composite activity, are scaled so that they sum up to the composite activity duration.
 - 7) *Worker-Only Activity Classes* The item remains stationary, one or more workers moves (change in location and/or orientation). Modeled in similar manner to complex activity classes (i.e., task-based), the only difference being no items are involved.

Panelized residential construction example: Of the 39 activity classes defined in Table 1, 10 are Type 1 (Attached Moving Worker Simple), one is Type 2 (Unattached Moving Worker Simple), 11 are Type 3 (Stationary Worker Simple), 10 are Type 4 (Complex), five are Type 5 (Composite), and two are Type 7 (Workers Only). An additional seven indirect activity classes are developed in support of the five composite activity classes. The entire set of activity classes, and their relationships, is shown in Fig. 5.

D. Identify activity types, establish sampling distributions

As previously defined, an activity class represents a particular ‘way’ workers perform some major process. As each activity class can cover a wide variety of scenarios (e.g., items of different sizes), however, it is necessary to further divide activity classes in order to obtain actual activities with which time/rate data can be associated. This leads to the idea of activity types for each activity class. Each activity type is a specific implementation of an activity class via a specific set of values for parameters associated with that class.

To establish activity types, it is necessary observe the various processing approaches in action for a large variety of scenarios, focusing on the details. For each activity class, the first step is to identify the relevant parameters: these can roughly be grouped under quantity of workers, relative motion direction, item attributes, worker attributes, and scenario attributes. Then, possible values for each attribute are established. The various combinations of possible attribute values then result in the activity types. Note that if a parameter is continuous or has an excessively large quantity of possible values, it may be necessary to discretize the possible range of values into a manageable quantity of ranges. For each range, the activity type then represents an average (or worst-case) scenario.

Following the above, a time or rate sampling distribution must be established for each activity type. This is then used to determine actual activity duration or rate during simulation execution. The data needed to establish these distributions can be obtained via lab-based measurements or observation and data recording of the process (*in situ* or video).

Panelized residential construction example: the following parameters and values were identified:

- Quantity of workers: 1-4
- Relative motion direction:
 - UNLOAD : unload panel from FRONT, BACK, LEFT, or RIGHT of stack.
 - CARRY: carry panel FWD (forward), BWKD (backward), LEFT, RIGHT, or TURN (rotate in place with panel).
- Item attributes: panel size (dimensions) and weight, whether reference face sheathed or not.
- Worker attributes: none. All workers considered identical.
- Scenario attributes:
 - UNLOAD: as each panel is taken from the top of the stack, stack height is constantly changing. Additionally, worker hand positions, postures, etc., were observed to vary with stack height. Reasonable similarity was found, however, for panels within the bottom, middle, and top portions of stack. Different unload activity types were thus specified for small (S), medium (M), and large (L) stacks.
 - INSTALL, FIX/BRC: eight scenarios were identified, each describing the already-finished panels to which panel P (being worked) will join. For example, P may join with a single finished panel on P's left side via a butt connection (Fig. 3(p)), or a corner joint. Or P may need to be squeezed in-between two already-finished panels, etc.

All of the above parameters, except for panel size and weight, were used to establish activity types (panel size and weight were not used because these can be directly correlated to the quantity of workers used). Based upon these parameters and values, 589 activity types were identified for the 39 top-level activity classes. These were derived as shown in Table 2.

Examples of particular activity types: and distribution data needed:

U5_BACKFRONT_2_L_SH: U5 unload from back or front of stack, 2 workers, low stack height, sheathed panel. Time distribution (sec.) needed.

C3_4_FWD: C3 carry, 4 workers, panel translating in forward direction. Translation rate (ft./sec.) distribution needed.

E. Improve Process Validity

At this point, physical processes are modeled via sequences of activity types. In other words, the process is obtained by stringing the activities together, one after another. Regardless of how accurate the individual activity type models are, however, this approach suffers from the fact that humans are not robots: they cannot perform one task or activity after another, without any breaks or other delays. Additionally, as humans get fatigued, task performance suffers and the activities themselves are performed at reduced rates.

While consideration of fatigue is beyond the scope of this work, simple methods can be used to account for momentary pauses and breaks. This can be done at three levels:

- 1) Short deterministic or stochastic reset times between specific tasks, to account for brief pauses and/or minor changes in hand positions, posture, etc.
- 2) Medium stochastic activity reset time in-between activities, to account for longer pauses (e.g., worker stretches, takes a quick breather before continuing, looks to see if supervisor is around, etc.) and/or major changes in hand positions, posture, etc.
- 3) Longer stochastic changeover time at start of first major process and in-between processes.

Panelized residential construction example: A task reset time of 2 seconds was employed between tasks where workers change grip or how a panel is held (e.g., U3_stk: reset time between workers pulling panel clear of stack and then raising/lowering panel). Activity reset time was randomly generated per a uniform distribution between 0 and 10 seconds = $U(0,10)$, except for in-between panel translate/rotate activities (C1_x, Cx): $U(0,5)$ was used for these. Process start/changeover time was randomly generated from $U(2,5)$. All of these parameters were established based upon analysis of video recordings of the panelized residential construction process.

F. Code-up activity classes, process modeling 'language'

To utilize the activity classes and types developed per the above in a simulation, they must be coded so they can be used in a simulation program (either commercial software calling these as routines, or within a stand-alone software program). Each activity class becomes a function: the collection of functions becomes the language used for both modeling and simulating the multi-worker physical processes. The most flexible approach is a stand-alone, object-oriented discrete-event simulation program, written using a high-level language such as C++. With this approach, the items and workers are objects in the simulation: they “know” and “track” their own location/orientation, and which items are associated with (seized by) which other items at any particular time. Additionally, each worker can keep a record of what moves he has made, with which other workers and what items, and at what times. These aspects simplify function definition and development, as well as provide a natural framework for obtaining the data which will be needed later for ergonomic assessment. Animation capability can also be incorporated into the simulation program, if desired.

Panelized residential construction example: Object-oriented modeling was employed, using C++. The process modeling language (functions) are shown in Table 3. All functions pass the panel object of concern: panels track their location/orientation, as well as which workers are associated with it. These worker objects, in turn, track their location/orientation at any time. Thus, the various parameter values needed by each function (quantity of workers, whether panel is sheathed or not, etc.) for a particular activity type can be determined from these objects directly: such data does not need to be passed in the function call. Higher-level functions have been incorporated for CARRY, LIFT, and DROP processes. Examples of single- and multiple-worker panel processing are provided in Fig. 6. An overall example animation of the simulated panelized residential construction process, using the simulation modeling approach and language described above, is shown in Fig. 7. A discrete-event panelized residential construction simulator, coded using C++ and utilizing the functions shown in Table 3, was

developed and utilized to perform the simulations. The simulator also generated animation statements which provided process animation using PROOF 3D software (Wolverine Software Corporation). Detailed descriptions of the simulator and animation capability are beyond the scope of this paper.

V. Ergonomic Assessment Methodology

A. Identify and model ergonomic tasks

In any complex, physical process employing multiple workers, there will undoubtedly be a large and varied set of loads imposed on the workers involved. As it is not possible to identify and model every one of these loads, those which are the most substantial (high risk exposures) can be isolated for detailed consideration: we refer to these as “ergonomic tasks”. To systematically identify and characterize ergonomic tasks, the activities established as described in Section 4 (or via a separate modeling exercise) must be studied in detail. Hierarchical task analysis, work sampling, and/or worker interviews can be used to obtain additional information regarding activity frequency, characteristics, item handling techniques, and physical demands .

Ergonomic task types are established first: each of these becomes one or more ergonomic tasks based upon whether or not workers perform the tasks in fundamentally-different ways for different parameters (e.g., relative item location).

Panelized residential construction example: A taxonomy of panelized wall construction activities was developed based upon video recordings and worker interviews for the construction of 10 different homes in the Washington, DC area [2]. Four ergonomic task types were identified: lifting, carrying, erecting, and moving. From these, eight ergonomic tasks were established, based upon different panel starting heights and alternative panel handling techniques. These tasks are shown in Table 4.

B. Develop ergonomic equations

For each ergonomic task, appropriate ergonomic assessment methods must be identified and/or developed. Because of the broad range of parameters (e.g., item length, mass, relative location, quantity of workers) which can be associated with a task, it is often infeasible to assess ergonomic risks for the entire range of each parameter that can occur during physical processing. To cope with this, models are developed for each task to predict ergonomic risk: the models consider only task-related parameters as predictors and not detailed body kinematics as this level of detail is not provided by the simulation. Once the models have been established, the relevant kinematic/kinetic data needed to parameterize each model can be obtained (i.e., from laboratory experiments). This “task-based” approach assumes that risks are comparable for each worker doing a given task. To simplify ergonomic output analysis, the continuous output of such models can be discretized and normalized to a small set of possible values, each indicating a different relative level of ergonomic risk.

Panelized residential construction example: Various ergonomic assessment methods ([29],[30],[31],[32]) were used to quantify relative ergonomic risks for each task with respect to panel mass and length [3] and the availability of an additional worker [33]. For each task type (i.e., lifting, erecting, carrying, and moving), a regression model was developed was of the following form:

$$Y = b_0 + b_1H_0 + b_2M + b_3L + b_4NW + \text{Higher order and interaction terms} \quad (1)$$

where Y is the outcome measure from the respective ergonomic assessment method, $b_0 - b_4$ are regression coefficients, and H_0 , M , L , and NW are the panel height (m), mass (kg), length (m), and the number of workers involved, respectively. Laboratory experiments to establish the regression coefficients involved tasks with different combinations of three panel lengths, two panel masses, and the availability of an additional worker. Final regression models are currently being identified and validated. By example, however, an equation for the Rapid Entire Body Assessment (REBA) score for L1K has been obtained as:

$$Y = 3.96 + 0.77H_0^{-1} + H_0^{-2} \cdot (-0.025 + 0.00027L - 0.0000076M) + L(0.017 + 0.026H_0) - 0.03H_0NW \quad (2)$$

Ergonomic output was post-processed to obtain a three-level output for a given task, using the common traffic light analogy (i.e., red, yellow, green). This approach (e.g., [34], [35]) allows the rather extensive detailed outputs across workers and tasks to be compiled and more easily interpreted. For example, probability or cumulative distributions of ergonomic assessments can be obtained across workers and/or crews for a given structure.

C. Correlate ergonomic tasks with activity classes

Each ergonomic task identified above will be represented in simulation process models as either (i) a particular activity class, or (ii) one or more tasks within a particular activity class. The manner in which each ergonomic task is represented is first determined. Following this, the function (activity class) code is modified so that for each ergonomic task the appropriate worker/item location/orientation data is recorded when the corresponding activity is executed.

Panelized residential construction example: The eight ergonomic tasks correlate to activity classes/tasks as shown in Table 4.

D. Generate motion data during simulation

As outlined in Section 4.6, a process plan must be generated for each item. This plan consists of a sequence of function calls, each of which executes the correct activity for that item, workers, and parameter values. During simulation, the functions are executed, in order, when the processing is to occur: this is accomplished via traditional discrete-event simulation logic. Each time a function is executed, motion data pertaining to that item and workers is written to a file for post-processing.

Panelized residential construction example: Table 5 shows the motion data output for the multi-worker panel processing example shown in Fig. 6(b). In this particular realization, panel #27 is being processed by workers 3, 5, and 6. Note that the second forward flat panel move of 412.2 inches (10.47 m) appears in four separate ergonomic tasks (120.0, 120.0, 86.1, and 86.1 inches). This results from a simulation subroutine which breaks-up long move activities into smaller ones, to facilitate the interaction of multiple workers and panels.

E. Process motion data to generate ergonomic assessments

Once the motion data for a given item, workers, activity class, and parameters has been generated, ergonomic measures can be calculated.

Panelized residential construction example: Some of the ergonomic assessment methods used are applicable to all ergonomic tasks, and REBA is one example. Thus, REBA scores and corresponding three-level outputs are presented for the multi-worker processing example of Fig. 6(b) and motion data of Table 5:

- L1K: 4.4 (Yellow)
- C1: 5.0 (Yellow)
- E1Kside: 5.2 (Yellow)
- E1Ktop: 4.5 (Yellow)

VI. DISCUSSION

The proposed approach and methodology for simulation modeling and ergonomic assessment of complex, multi-worker physical processes was successfully applied to panelized residential construction. This exercise showed the application of these items to be relatively straightforward. The main difficulty, however, lies in the sheer volume of work required. As witnessed through the example, extensive study and effort is needed on four fronts:

- Modeling the process details: identification of processing alternatives, activity classes, and activity types. The process must be observed in action, whether *in situ* or via video recordings, for a very large number of scenarios.
- Establishing sampling distributions for activity types. As previously described, there were 589 distributions to generate for the panelized residential construction process. Laboratory experiments or video analysis were needed to generate the necessary data

for each of these. In the latter case, the time required for each may be significant as the observations must be located in the video tracks (though this can be minimized by going through each video in advance to determine what activity types occur and when).

- Coding up the activity classes and developing the process modeling language. This was a major coding effort, resulting in over 8500 lines of C++ code. Extensive effort was also needed to code-up a test simulation facility, to use for debugging.
- Performing the laboratory experiments to establish the ergonomic assessment models.

Overall, application of the proposed methodology and approach for simulation modeling and ergonomic assessment of complex, multi-worker physical processes to panelized residential construction took about 2 person-years. Additional time was needed to develop the simulator itself and animation capability (not described in this paper). Substantial time and effort is thus necessary to utilize the proposed methodology and approach. Of particular note is the need for 3D animation to support simulation modeling. Though not inherently necessary for executing the proposed approach and methodology, the panelized residential construction example indicated that it would be extremely difficult to code-up the activity functions without having animation capability for code verification and debugging.

Regarding modeling validity and ergonomic assessment, some limitations are inherent in our approach. Though the task-based approach to ergonomic risk assessment being used is common and generally accepted (e.g., [36], [37], [38], [39]), it is not without limitations. For example, differences in worker anthropometry are not accounted for, though exposures for a range of workers are available from the noted lab studies. Further, time-dependent effects of exposures (e.g., related to the sequencing of tasks) are not incorporated. In large part, these limitations result from a lack of good contemporary analysis tools. As future research provides these tools, though, they can easily be incorporated. Our approach to risk assessment also focuses on the fundamental tasks associated with the given multi-worker physical processing scenario. Other tasks having lower levels of exposure are not examined, but future work could more formally assess and include these additional tasks.

While the current approach provides detailed assessments of ergonomics risks, there are challenges in specific interpretations of such model-based outputs. In general, it is unclear, based on current evidence, how best to integrate ergonomic exposures across tasks, over time, and/or at the crew level. There is insufficient evidence to guide, for example, how to compile diverse assessments obtained from multiple ergonomic assessment tools and/or for risks at different body regions. Similarly, while cumulative (or accumulated) loading appears to be an important exposure/risk metric (e.g., [40], [41]), a specific quantitative approach to calculating a cumulative load is yet to be developed (e.g., [42], [43]). Fatigue, whether at the whole-body or more localized levels, is another aspect that is not currently incorporated. At the crew level, there is again limited evidence to guide interpretation (e.g., is it better to have one worker with relatively high risk and another relatively low vs. two workers with average risk?). Over time, however, as effective approaches are identified, each of these current limitations can be addressed by integrating additional algorithms into the system or through compilation/processing of the system outputs. Furthermore, future improvements specifically in

digital human modeling may obviate, or at least reduce, the need for detailed, time-consuming lab studies as were used here.

Finally, the potential problem of coordination between the simulation and ergonomic sides of the proposed approach and methodology must be kept in mind. Because this work requires expertise in each of these areas, there will undoubtedly be both simulation and ergonomics experts involved: effort will be required to ensure that these parties can work together in as seamless and productive a manner as possible. In the panelized residential construction effort, for example, the process analysis and modeling exercise was in fact performed twice: once from the ergonomics side and again from the simulation modeling side. Additional effort was then required to 'combine' the two models into one (see Table 4). It is believed that some duplication of effort due to the above-stated reasons is unavoidable. Steps to minimize the impact and adverse effect of such efforts, however, can and should be planned into the implementation process.

VII. CONCLUSIONS

In this paper, a generic approach and methodology for simulation modeling and ergonomic assessment of complex, multi-worker physical processes was presented. These items allow us to simulate and perform ergonomic assessment for processes where this would otherwise be unattainable. The approach and methodology was employed and demonstrated for the panelized residential construction process. This exercise showed that the proposed approach and methodology are straightforward, but also require substantial time and effort to implement (multiple person-years). This level of effort is unavoidable, however: similar levels of effort are routine for large-scale simulation projects.

The proposed approach and methodology can be applied to any problem involving complex, multi-worker physical processing. Example areas include manufacturing plants, warehouse facilities, shipyard operations, road construction, and military setup operations (e.g., artillery, bridges, field hospitals, etc.), to name a few. In any event, the approach and methodology should only be applied to processes having a long lifespan, due to the time and effort involved. Additionally, due to the need to study and analyze existing processes, it cannot be used for strictly to-be systems.

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Figure 1. Example of panelized residential construction. Workers are unloading a wall panel: two panel stacks are visible in the background.

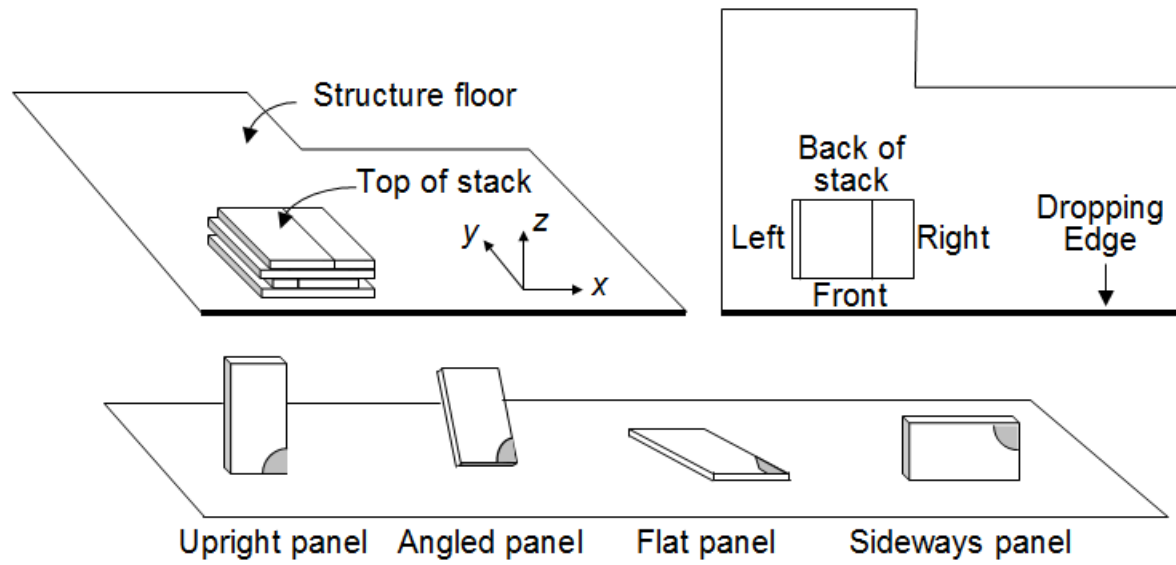


Figure 2. Orientation terminology used for modeling and simulation of panelized residential construction processes.

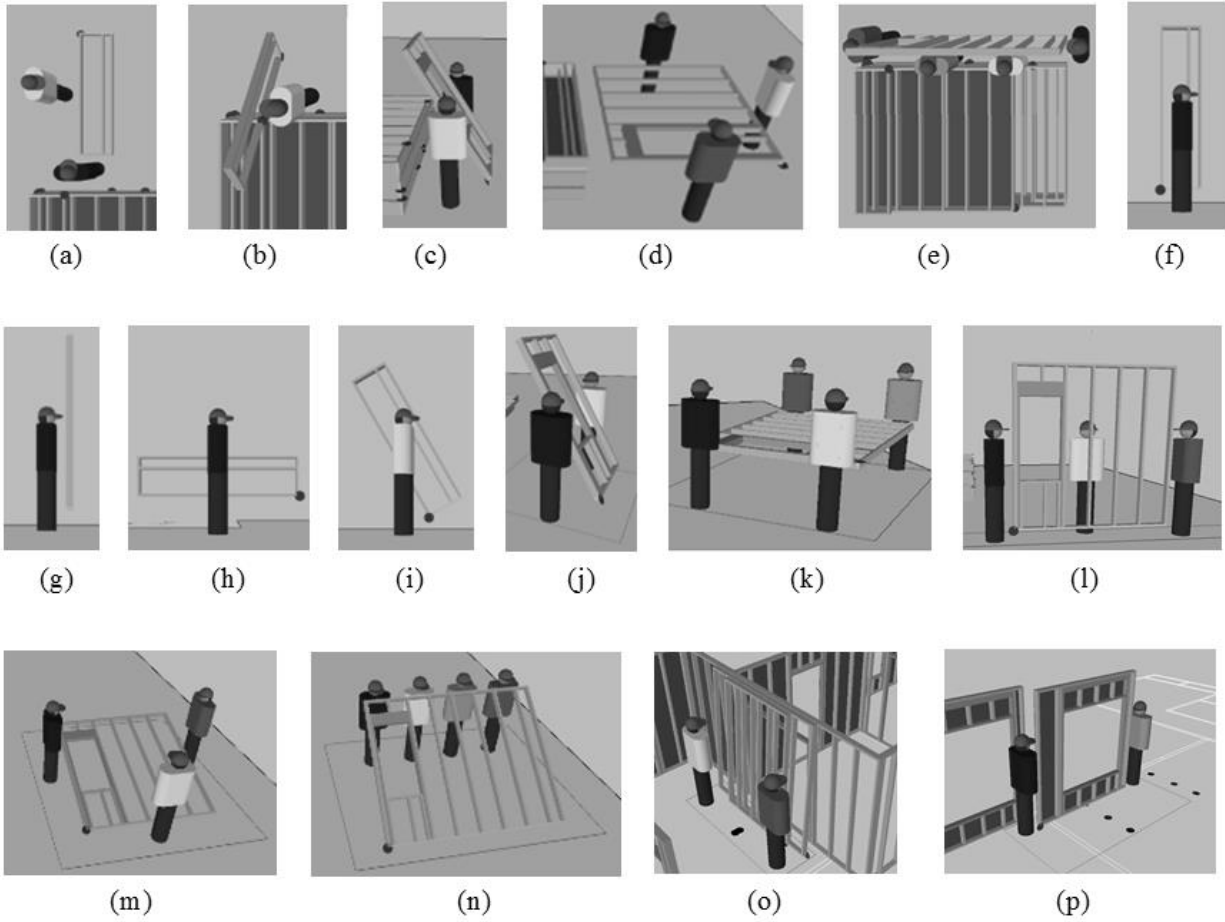


Figure 3. Examples of simulated activity classes (activities) for panelized residential construction: (a) U1_1, (b) U1_4, (c) U2, (d) U3, (e) U5, (f) C1_1, (g) C1_2, (h) C1_3, (i) C1_4, (j) C2, (k) C3, (l) C4, (m) TIP, (n) ERECT, (o) STORE, (p) INSTALL

Single Worker

I) Unload helper needed

Very small carry distances: U1_1→L1_2→C1_2→D1_2→INSTALL→FIX_BRC

Small carry distances:

U1_1→L1_1→RW→C1_1→D1_1→RW→INSTALL→FIX_BRC

Medium carry distances:

U1_1→RP1_2→L1_3→RW→C1_3→D1_3→RW→E1_3→INSTALL→FIX_BRC

Large carry distances:

U1_1→L1_1→RW→RP1_1→C1_4→D1_4→RW→E1_4→INSTALL→FIX_BRC

II) No unload helper needed

Very small carry distances: U5
U1_5 > L1_2→C1_2→D1_2→INSTALL→FIX_BRC

Small carry distances:

U5
U1_5 > L1_1→RW→C1_1→D1_1→RW→INSTALL→FIX_BRC

Medium carry distances:

U5
U1_5 > RP1_2→RW→L1_3→C1_3→D1_3→RW→E1_3→INSTALL→FIX_BRC

Large carry distances:

U5
U1_5 > L1_1→RW→RP1_1
U1_4→RW → C1_4→D1_4→RW→E1_4→INSTALL→FIX_BRC

Multiple (2-4) Workers

Small carry distances: U5→Lu→C4→Du→C5→INSTALL→FIX_BRC

Carry distance no more than x ft.,

panel weight no more than y lb: U2→C2→Da→ERECT→INSTALL→FIX_BRC

Medium-large distances: U3
U4 > C3→TIP→ERECT→INSTALL→FIX_BRC

Figure 4. Overall processing alternatives, specified via activity classes, for panelized residential construction via direct panel install.

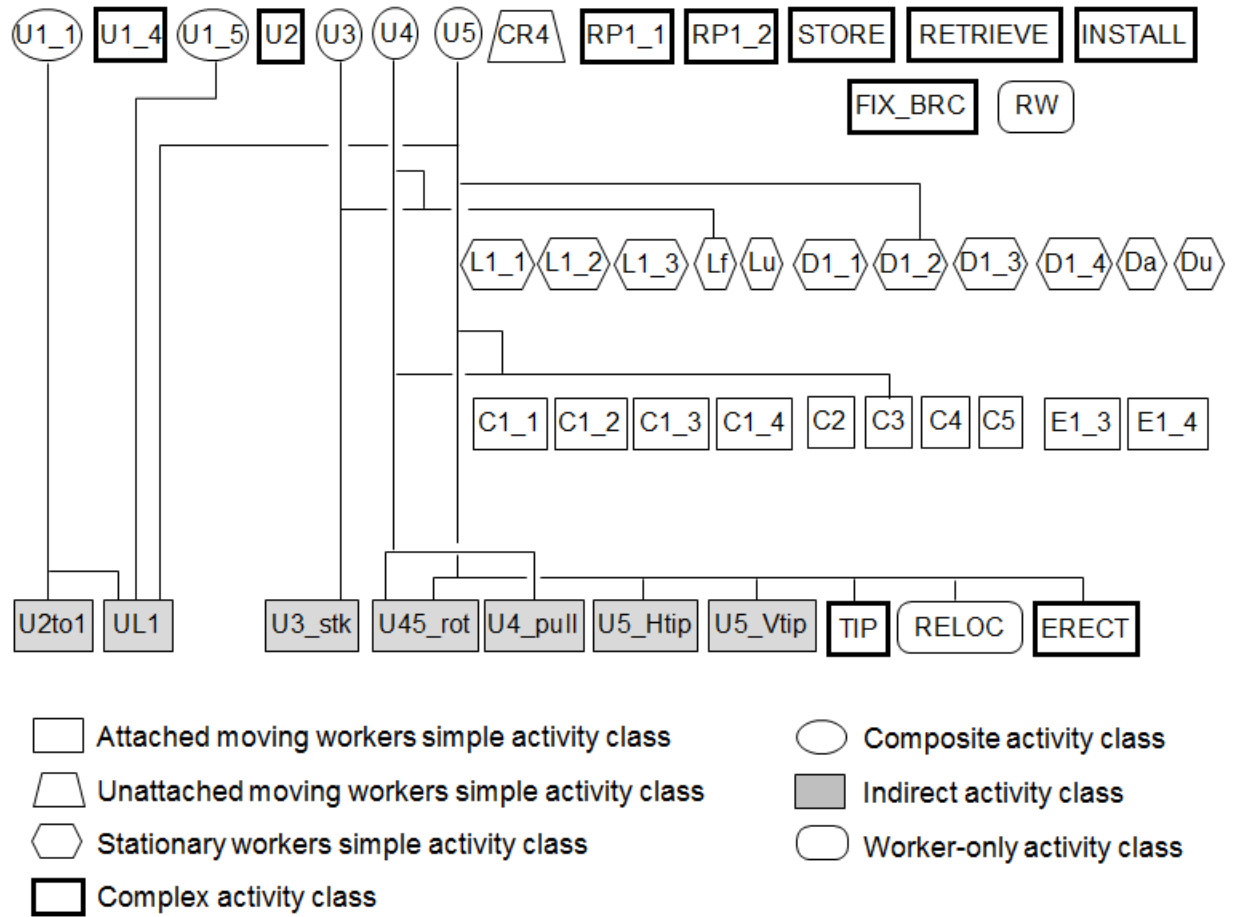


Figure 5. Activity classes used for modeling panelized residential construction.

U1_1(Panel);	//Unload the panel from stack, using a helper
LIFT(Panel,L1_1_);	//Lift upright panel off of floor to C1_1 carry height
RW(Panel,RIGHT);	//Worker turns body 90° cw, so upright
	//panel at worker's left side
CARRY(Panel,C1_1_,FWD,48);	//Walk (worker carrying panel) forward 48 inches
CARRY(Panel,C1_1_,TURN,-90);	//Turn (worker and panel) 90° cw
CARRY(Panel,C1_1_,FWD,150);	//Walk forward 150 inches
CARRY(Panel,C1_1_,RIGHT,10);	//Move RIGHT (sideways) 10 inches
DROP(Panel,D1_1);	//Lower upright panel to the ground
RW(PPanel,LEFT);	//Worker turns (90° ccw) to face panel once again
INSTALL(Panel);	//Install the upright panel
FIX_BRC(Panel);	//Fix and brace the panel

(a)

U3(Panel,BACK);	//Flat panel unload from back side of stack
CARRY(Panel,C3_,FWD,30);	//Walk (workers carrying flat panel) forward 30 in.
	//Note: walking AWAY from back side of stack
CARRY(Panel,C3_,TURN,80.4);	//Turn (workers and panel) 80.4° ccw
CARRY(Panel,C3_,FWD,412.2);	//Walk forward 412.2 inches
CARRY(Panel,C3_,TURN,-80.4);	//Turn 80.4° cw
CARRY(Panel,C3_,FWD,18);	//Walk forward 18 inches
TIP(Panel);	//Tip forward edge of panel down to contact floor
ERECT(Panel,C1_1_,TURN,45);	//Tip rear edge of panel up until panel upright
LIFT(Panel,Lu_);	//Lift upright panel straight up off of floor
CARRY(Panel,C4_,LEFT,24);	//Carry upright panel LEFT 24 inches
DROP(Panel,Du_);	//Lower upright panel back down to floor
INSTALL(Panel);	//Install the upright panel
FIX_BRC(Panel);	//Fix and brace the panel

(b)

Figure 6. Examples of residential construction panel processing specified via high-level modeling language: (a) single worker: unload helper used and small panel carry distance, (b) multiple workers: medium-large carry distance.

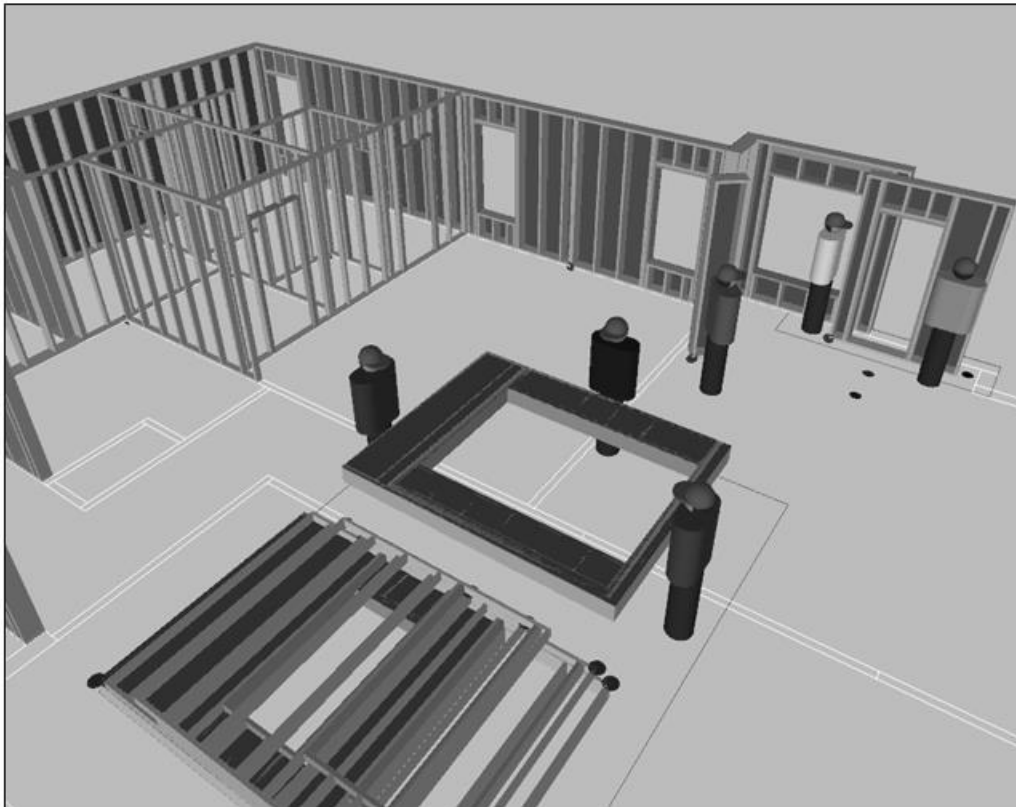


Figure 7. Example of animation of simulated panelized residential construction, showing UNLOAD, CARRY, and INSTALL processes.

Table 1. Top-level activity classes used for modeling panelized residential construction.

Major Process	Activity Class	Description
UNLOAD	U1_1	Single-worker panel unload: worker pulls top panel off of stack from stack's back side (with helper) until panel falls flat to ground. Worker then tips panel to upright position.
	U1_4	Single-worker panel unload: worker pulls top panel partially off of stack from stack's back side, until bottom of panel tips down, contacts floor. Worker then tips panel sideways on stack, then carries angled sideways panel away from stack.
	U1_5	Single-worker panel unload from ground (stack gone): worker tips panel lying flat on floor to upright position.
	U2	Angled panel unload: workers partially tip panel off of back side of stack, to C2 position (2 workers only).
	U3	Flat panel unload: pull top panel off of stack from stack's back, L or R side; raise/lower to C3 position (2-4 workers).
	U4	Flat panel unload following rotation: rotate top panel 90° cw (ccw) on stack, pull panel completely off of left (right) side of stack, raised/lower panel to C3 position (2-4 workers).
	U5	Tip unload: pull top panel off of stack (back, front, L or R side) until panel tips, bottom plate hits floor. Continue rotating panel to upright position (C5) resting on floor (1-4 workers).
CARRY	C1_1	Single-worker upright panel carry (xy translation or rotation), panel at worker's side.
	C1_2	Single-worker upright panel carry (xy translation or rotation), panel in front of worker.
	C1_3	Single-worker sideways panel carry (xy translation or rotation): panel at worker's side.
	C1_4	Single-worker angled panel carry (xy translation or rotation), panel at worker's side, carried over worker's shoulder.
	C2	Angled panel carry (xy transl. or rot.), 2 workers only.
	C3	Flat panel carry (xy transl. or rot.), 2-4 workers.
	C4	Upright panel carry (xy transl. or rot.), 2-4 workers.
	C5	Upright panel slide on floor (xy trans. or rot.), 2-4 workers
	CR4	Upright panel carry (simultaneous xy transl./rot.), 2-4 workers.
	L1_1	Lift upright panel at worker's side, on floor, to C1_1 position.
	L1_2	Lift upright panel in front of worker, on floor, to C1_2 position.
	L1_3	Lift sideways panel at worker's side, on floor, to C1_3 position.
	Lf	Lift flat panel, on floor, to C3 position (2-4 workers).
	Lu	Lift upright panel, on floor, to C5 position (2-4 workers).

Table 1. (cont.)

Major Process	Activity Class	Description
CARRY	D1_1	Lower upright panel at worker's side (C1_1 position) to floor.
	D1_2	Lower upright panel in front of worker (C1_2 position) to floor.
	D1_3	Lower sideways panel at worker's side (C1_3 position) to floor.
	D1_4	Lower angled panel at worker's side (C1_4 position) to floor.
	Du	Lower upright panel, at C4 position, to floor (2-4 workers).
	Da	Lower angled panel, at C2 position, to floor (2-4 workers).
	RP1_1	Single worker lift/rotate upright panel at worker's side (following L1_1) to C1_4 position.
	RP1_2	Single-worker rotate upright panel, resting on floor, to sideways position (on floor).
	RELOC	Relocate worker(s), upright panel, 3-4 workers. Middle worker (if 3 workers) or workers (4 workers) walk(s) around panel to same location on other side of panel.
	TIP	Flat panel tip: lower forward edge (bottom plate) of panel in C3 position down to contact floor; reposition middle worker (if 3 workers) or workers (4 workers).
	E1_3	Single-worker panel erect: sideways panel on floor, rotate panel about one corner until upright.
	E1_4	Single-worker panel erect: angled panel corner resting on floor, rotate panel about corner until upright.
	ERECT	Panel erect: raise rear end of panel having forward edge on floor until panel upright (2-4 workers).
STORE	RW	Rotate worker in xy plane.
	STORE	Tip upright panel to lean against finished wall for temporary storage (1-4 workers).
RETRIEVE	RETRIEVE	Remove upright panel being stored temporarily at wall: tip to upright position, back away from wall slightly (1-4 workers).
INSTALL	INSTALL	Slide, jog and position upright panel, resting on floor, into final location/orientation in structure (1-4 workers).
FIX/BRACE	FIX_BRC	Fix and brace installed panel (1-4 workers).

Table 2. Activity types for each activity class, panelized residential construction.

Activity Class	Parameters ^a	# of Activities	Sampling Dist. Variable
U1_1, U1_4	(L, M, H SH) x (S/U panel)	6	Time
U1_5	S/U panel	2	Time
U2	(floor, L, M, H stack height) x (S/US panel)	8	Time
U3	(B, L/R stack unload) x (2-4 W) x (L, M, H stack height) x (S/US panel)	36	Time
U4	(L/R stack unload) x (2-4 W) x (L, M, H stack height) x (S/US panel)	18	Time
U5	(B/F, L/R stack unload) x (1-4 W) x (L, M, H stack height) x (S/US panel)	48	Time
C1_1, C1_3, C1_4	(move FW, L/R or TURN) x (S/US panel)	6	Trans. or rot. speed
C1_2	(move FW, L/R, BW, or TURN) x (S/US panel)	8	Trans. or rot. speed
L1_1, L1_2, L1_3, RP1_1, RP1_2, D1_1, D1_2, D1_3, D1_4, E1_3, E1_4	S/US panel	2	Time
RW	LEFT (90° ccw), RIGHT (90° cw)	1	Worker rot. time
C2	(move FW, BW, L/R, or TURN) x (S/US panel)	8	Trans. or rot. speed
C3, C4, C5	(move FW, BW, L/R, or TURN) x (2-4 W) x (S/US panel)	24	Trans. or rot. speed
CR4	((2 W) x (2 panel lengths) x (3 transl. distances) x (3 rotation angles) + (3,4 W) x (3 transl. distances) x (3 rotation angles)) x (S/US panel)	72	Time
RELOCATE	(3,4 W) x (wide, narrow) x (S/US panel)	8	Time
Lf, Lu, Du, Da, TIP, ERECT	(2-4 W) x (S/US panel)	6	Time
STORE, RETRIEVE	(1-4 W) x (S/US panel)	8	Time
INSTALL	((single worker) x (3 sc.) + (2-4 W) x (8 scenarios)) x (S/US panel)	54	Time
FIX_BRC	((single worker) x (3 scenarios) + (2 worker locations) x (8 scenarios) + (3 worker locations) x (8 scenarios) + (4 worker locations) x (8 scenarios)) x (S/US panel)	150	Time

^aS/U = sheathed/unsheathed, W = workers, L = low, M = med, H = high, B = BACK, F = FRONT, L/R = LEFT/RIGHT, FW = FORWARD, BW = BACKWARD

Table 3. Activity class functions for modeling panelized residential construction.

Function	Parameters (besides panel* P)
U1_1(panel* P)	(none)
U1_4(panel* P)	(none)
U1_5(panel* P)	(none)
U2(panel* P)	(none)
U3(panel* P, int dir)	dir = BACK, LEFT, or RIGHT
U4(panel* P, int dir)	dir = BACK, LEFT, or RIGHT
U5(panel* P, int dir)	dir = BACK, FRONT, LEFT, or RIGHT
CARRY(panel* P, int ctype, int dir, float dist_angle)	ctype = C1_1_, C1_2_, C1_3_, C1_4_, C2_, C3_, C4_, C5_ dir = FWD, BKWD, LEFT, RIGHT, TURN dist_angle = translation distance (dir = FWD, BKWD, LEFT, RIGHT) or rotation angle, ccw +ve (dir = TURN)
CR4(panel* P, int dir, float dThz, float dist)	dir = LEFT or RIGHT dThz = panel free end rotation angle, ccw +ve dist = translation distance
LIFT(panel* P, int ltype)	ltype = L1_1_, L1_2_, L1_3_, Lf_, Lu_
DROP(panel* P, int dtype)	dtype = D1_1_, D1_2_, D1_3_, D1_4_, Da_, Du_
TIP(panel* P)	(none)
ERECT(panel* P)	(none)
ERECT_1(panel* P, int etype)	etype = E1_3_, E1_4_
RP1_1(panel* P, float thVo, float thV, float end_height)	thVo = starting panel orientation (0° = upright, 90° = sideways) thV = final panel angle end_height = height of lowest point on panel following rotation
RP1_2(panel* P, int dir)	dir = LEFT or RIGHT
RW(panel* P, int dir)	dir = LEFT (worker rotates 90° ccw) or RIGHT (worker rotates 90° cw)
RELOCATE(panel* P, int type int dir)	type = NARROW or WIDE dir = walking dir (3 workers only), LEFT or RIGHT
STORE_P(panel* P)	(none)
RETRIEVE_P(panel* P)	(none)
INSTALL_P(panel* P)	(none)
FIX_BRC(panel* P)	(none)

Table 4. Ergonomic tasks and corresponding activity classes, panelized residential construction.

Ergonomic Task		Activity Classes
Identifier	Description	
L1G	Lift flat panel straight up from ground to knuckle height (worker standing)	Lf
L1K	Lift flat panel off of stack to C3 position	Task within U3_stk , U4_pull
L2G	Lift flat panel from floor to C2 position	Task within U2
L2K	Lift flat panel off of stack to C2 position	Task within U2
C1	Carry flat panel	C3 , dir = FWD, BKWD, LEFT, RIGHT
C2	Angled panel carry	C2 , dir = FWD, BKWD, LEFT, RIGHT
M1	Move (slide) upright panel along floor, in direction parallel to panel's length	C5 , dir = LEFT, RIGHT
E1GTop	Erect flat panel from ground, top (middle) worker(s), 3 or 4 workers	ERECT (multiple workers)
E1GSide	Erect flat panel from ground, side workers	UL1 (single worker), ERECT (multiple workers)
E1KTop	Erect flat panel from knuckle height, top (middle) worker(s), 3 or 4 workers.	TIP + ERECT , multiple workers (single worker: not applicable)
E1KSide	Erect flat panel from knuckle height, side workers	TIP + ERECT , multiple workers (single worker: not applicable)

Table 5. Example of motion data generated via simulation of panelized residential construction.

Time	Task	#	Length	Weight	Sheath	Z Loc	dX	dY	dZ	dist	qty	IDs
349.0	L1K	p27	100.0	214.3	2	69.0	0.0	0.0	-37.0		3	5 3 6
367.4	C1	p27	100.0	214.3	2	32.0	0.0	30.0	0.0	30.0	3	5 3 6
390.3	C1	p27	100.0	214.3	2	32.0	-118.3	19.9	0.0	120.0	3	5 3 6
393.2	C1	p27	100.0	214.3	2	32.0	-118.3	19.9	0.0	120.0	3	5 3 6
396.1	C1	p27	100.0	214.3	2	32.0	-84.9	14.3	0.0	86.1	3	5 3 6
398.2	C1	p27	100.0	214.3	2	32.0	-84.9	14.3	0.0	86.1	3	5 3 6
426.5	C1	p27	100.0	214.3	2	32.0	0.0	18.0	0.0		3	5 3 6
432.9	E1Kside	p27	100.0	214.3	2	32.0	0.0	0.0	0.0		2	5 3
432.9	E1Ktop	p27	100.0	214.3	2	32.0	0.0	0.0	0.0		1	6

4.3. Using a lean approach to enhance panelized construction

Shewchuk JP, Nussbaum MA, Gopinath S: A lean approach and methodology for panelized residential construction. Submitted to the Journal of Construction Engineering and Management.

ABSTRACT

A newly-established approach to residential construction is the use of prefabricated wall panels. In this approach, wall panels are produced and arranged into stacks at a factory, then sent to the job site where construction workers unload, move, and install them. This alternative to traditional 'stick-built' construction can result in faster construction, higher build quality, and reduced cost, as panel construction takes place under controlled factory conditions. On-site construction becomes more difficult, however, as the panels can be extremely large and heavy. This paper presents an approach and methodology for panelized residential construction which implicitly considers this aspect of the problem. The entire process is addressed, from panel design to on-site construction, based upon lean concepts and principles. This results in a set of plans for each stage of the process, which work together to ensure that construction is well-planned, safe, and manageable for the workers. Preliminary results from a field study are reported: these show that the approach/methodology simultaneously improves productivity (construction lead time and stack quantity), worker safety, and construction workload.

INTRODUCTION

Panelized construction has become an accepted alternative to traditional 'stick-built' construction in the residential housing industry. In this approach, house walls are sub-divided into 'panels': these are then manufactured in a factory, bundled into stacks, and the stacks transported to the job site. Stacks are then moved to the structure subfloor, where workers unload the panels, move them to their final locations, and install them. This approach can result in faster construction and higher build quality as compared with stick-built homes. This is due primarily to the fact that the panels, being made in factories and under controlled conditions using computer-generated plans driving CNC equipment, are extremely well-made (much more accurate dimensions and tolerances, nailed together more accurately, etc.). Additionally, the need for on-site panel adjustment or modifications is minimized. On-site labor costs are also reduced: by moving the manufacturing portion of construction upstream to the factory, the remaining process is de-skilled and experienced framers can be replaced with semi-skilled manual laborers. A study performed by the Building Systems Council (National Association of Home Builders 2009) indicated that a 2,600 sq. ft. home built via panelized construction used 37% of the worker-hours required using traditional stick-built methods, while at the same time using 26% less lumber, creating 76% less waste, and reducing total framing costs by 16%. Panelized construction also reduces vandalism and, by getting the structure under roof and weather tight more quickly, the effects of adverse weather conditions.

While panelized construction has many advantages, it also has the inherent problem of making construction more difficult for the workers. Their job is now simply to unload, move and erect

the panels, which can be extremely large and heavy (e.g., 8 ft. high x 16 ft. long and weighing over 250 lb). This problem is further exacerbated by the fact the panelized construction in practice is handled in similar manner to stick-built: get the materials to the job site and let the field crew worry about construction. The focus is on efficient production, stacking, and transport of panels, which results in stacks and panels which are often extremely difficult to work with at the job site. Overall, the performance increases attained via the panelized approach may be accompanied by increased worker injury, builders' liability, and exposure to worker's compensation claims.

This paper presents an approach and methodology for panelized residential construction which implicitly considers the above aspect of the problem. The approach is based upon lean concepts and principles, and addresses the entire process from panel design through stacking and all the way to on-site construction. This results in a set of plans for each stage of the process, which work together to ensure that on-site construction is well-planned, safe, and manageable for the workers. Section 2 reviews the literature, while the basic modeling framework is presented in Section 3. Detailed descriptions of how panelized residential construction is done using both existing and the proposed approaches are provided in Sections 4 and 5: the methodology used for the proposed approach is described in detail in Section 6. The methodology is explained with reference to an actual house which was designed and built using the proposed approach and methodology. Section 7 provides and discusses the field study results: concluding remarks and future work are provided in Section 8.

LITERATURE REVIEW

While panelized construction has become an accepted alternative for building residential homes, the literature shows surprisingly little interest in the approach. Shewchuk *et al.* (2009) present an overall approach for designing and planning for panelized residential construction which takes ergonomic considerations into account. The approach is based upon lean ideas, and addresses each step of the process but in limited detail. The lean approach and methodology presented here builds upon the basic steps and ideas of that paper, but is much more comprehensive and detailed and addresses several steps in a different manner. The only other effort which considers panelized residential construction in an end-to-end manner is Nussbaum *et al.* (2009). This paper focuses on the ergonomics associated with on-site construction, but also gives a high-level view of the various design problems associated with panelized residential construction and how a decision-support system could be implemented to tackle the problems in an integrated manner. No details on the design problems or overall methodology were provided in that work, however.

The most detailed work to-date in the area of panelized residential construction is Shewchuk and Guo (2012). This paper addresses three aspects of panelized residential construction: panel stacking, panel sequencing, and stack locating. Algorithms are developed for these problems based upon lean principles: computational experiments are then performed comparing the performance of the proposed algorithms against manual solution and solution via a commercial software package. The overall results indicated significant improvements using the proposed algorithms: 25% fewer stacks, an 11% reduction in total panel carrying distance, and the elimination of all unavoidable free-standing panels (require additional bracing) and 'squeeze

fit' panels (increased installation difficulty). The lean approach and methodology presented here builds upon that paper, in order to consider the entire end-to-end process in similar manner. Guo (2010) also considers the panel stacking, panel sequencing, and stack location problems in panelized residential construction. This work suffers from several shortcomings, however, as described by Shewchuk and Guo (2012).

Several other works are reported that do not deal with panelized residential construction directly, but do address particular problems associated with residential construction. Hegazy *et al.* (1999) describe a model and genetic algorithm for locating items at construction sites. Such items could include panel stacks, but additional details pertaining to stack formation and location are not discussed. Jang *et al.* (2007) similarly employ a genetic algorithm to determine where to place construction materials to minimize repositioning. Again, panel stacks are not explicitly considered. Hu (2005) tackles the construction planning process for prefabricated buildings by using geometric reasoning to reverse the disassembly process, thus obtaining the construction process. The details of stack formation, drop-off, etc., however, are not considered. Nguyen (2005) proposes a framework, based upon solid modeling, that can automatically generate construction activity sequences. Again, however, panel stacking details are not considered.

The remaining related works can be divided into two categories: lean construction and construction simulation. Lean construction looks at the application of lean concepts and tools in the construction industry to improve processes, cut costs, and improve health and safety (Aziz and Hafez 2013). Marhani *et al.* (2013) review the literature to provide fundamental knowledge of LC and highlight the barriers of its implementation, while Salem *et al.* (2005) suggest that adapting lean techniques eliminates waste and increases profit. Particular attention is paid to the application of 5S to construction. This term refers to a set of five activities which result in an uncluttered, clean, and organized workplace: benefits from 5S implementation include improved safety and quality, reduced lead times and improved morale of the workers and teams (Hirano 1996; Monden 2012). Using factor analysis on data collected via questionnaires, Sawacha *et al.* (1999) provided support to the notion that sites which are tidy and well planned (layout) are more likely to provide a high level of safety performance. These works do not refer specifically to panelized residential construction, however.

The use of simulation as a tool to assist the construction process has been used since the 1970s (Halpin 1973; AbouRizk 2010). AbouRizk *et al.* (2011) envisioned a time when the realization of a construction project takes place in a virtual world, with all the details of its scope and constraints defined before or in parallel to its realization in the real world. Based on case studies, they note that simulation should be used as an opportunistic tool to be introduced in appropriate applications and situations, rather than a universal tool for all construction management applications. Similarly, specific simulation methodologies proposed for construction, such hybrid simulation modeling (Alzraiee *et al.*, 2015) and the Simplified Discrete-Event Simulation Approach (Lu 2003), enhance project planning and modeling but are not applicable in all scenarios. These ideas are reflected in the proposed lean approach and methodology, which makes heavy use of discrete simulation for the final stage of the process (on-site construction) only. Simulation of the construction process, where prefabricated wall

panels are used, has been developed as part of the RUBICON project (Stouffs *et al.* 1994). Here, task planning is done based on resource availability, construction elements (wall panels, etc.) and the construction sequence, to develop motion plans for panel handling and installation via robotic cranes. Panel stacking, sequencing, and other aspects of panelization are required as inputs and are not generated in this approach. Additionally, humans are not used for panel handling and installation. Dagan and Isaac (2015) developed a methodology for analyzing and, if necessary, adjusting the planned locations of workers on construction sites, in order to prevent the hazards that occur due to an excessive proximity between different workers. This work does not consider multiple workers working together on multiple large objects (i.e., panels) simultaneously, however.

MODELING FRAMEWORK

The various terms used to describe the panelized residential construction process are illustrated in Figure 1. Panels are defined relative to a local reference point, at the bottom left corner of each panel's reference face. This point is also used to specify panel locations and orientations in stacks and in the finished structure. Each panel, at its final location in the structure, has an *install vector* which indicates the direction from which the panel is installed (vector points towards workers installing the panel). Stacks are comprised of multiple layers, each of which can hold one or more panels. Each panel has a particular location and orientation in its layer: orientation is specified via whether the top surface of the panel is the panel's reference face or not (*stack face*: panel face-up vs. face-down) and the angle made between a panel's bottom plate and the stack's reference edge (*stack angle*: 0°, 90°, 180°, or 270°). Stacks are dropped off on the structure sub-floor, with their reference edge parallel and closest to a single edge of the structure particular edge (*dropping edge*). Stack length, depth, and height must all be within maximum limits.

Following stack unload, panels can be processed in one of two ways:

- *single-stage panel processing (direct-install panels)*: carry to install location, install the panel, then fix (attach) and brace the panel, all in one continuous process.
- *multi-stage panel processing (indirect-install panels)*: carry the panel to a temporary storage location (e.g., store on floor, lean against a finished wall) one or more times, finish later (carry to install location, install, fix/brace).

For any given structure, panelized residential construction is defined via the following plans:

- *panelization plan*: how structure walls are to be divided into panels.
- *stacking plans*: how panels are formed into stacks.
- *stack transport plans*: where and when stacks are dropped off on the structure sub-floor.
- *construction plans*: how many workers work with each panel, panel unload and install sequence, location of temporary storage areas, and install vector for each panel.

To establish how good a given set of plans is, many performance measures and objectives can be used. Factory objectives include minimizing the total time (cost, effort) to manufacture and stack the panels, as well as total material cost. The stack transport objective is typically to minimize the quantity of trips to the job site. As quantity of trips (truckloads) is directly proportional to the quantity of stacks, we can instead look at quantity of stacks. Construction objectives include minimizing construction lead time, quality problems, and worker-related injuries and lost man hours. While we discuss all of these factors to varying extents in this paper, the proposed approach and methodology focuses on the following measures (i) quantity of stacks, (ii) construction lead time, and (iii) ergonomic impact. For estimating the ergonomic impact of a given set of panelization, stacking, and stack transport plans (i.e., prior to construction), surrogate measures are employed. Three such measures, introduced by Shewchuk and Guo (2012), are used in describing the proposed approach and methodology:

- i) *Total weighted panel material handling distance*. Overall measure of the effort associated with moving a set of panels from one location to another, taking into account that larger panels are more difficult to work with. For a given panel i being moved from its 'A' location (e.g., stack) to its 'B' location (e.g., install location), we calculate this effort as (weight of panel i) $\times$ (total rectilinear distance between A and B). Summing up these values for all panels $i \in Q$ gives $TWMHD_{A \rightarrow B}(Q)$ = total weighted material handling distance, moving all panels in Q from A to B.
- ii) *Fittability*. Overall measure of how much work is needed to jog, slide, nudge, or otherwise manipulate panels into their final location in the structure once moved. For a given panel, fittability is zero if the panel must be squeezed in-between two (or more) already-completed panels; it is one otherwise. Summing up these (0,1) values for all panels, and accounting for panels for which squeeze fits are unavoidable, provides an overall measure of fittability.
- iii) *Connectivity*. Overall measure of how much work is needed to provide temporary bracing for each panel, so that it remains upright. For a given panel, connectivity is zero if no connecting panels are already completed, it is one otherwise. Summing up these (0,1) values for all panels, and considering that the first panel installed always requires bracing, provides an overall measure of connectivity.

For estimating ergonomic impact based upon construction plans, worker utilization and various ergonomic indices can be used.

CURRENT APPROACH TO PANELIZED RESIDENTIAL CONSTRUCTION

As outlined in the Introduction, the current approach to panelized residential construction results in stacks and panels which can be extremely difficult to work with at the job site. This approach is explained in more detail as follows.

The lead contractor (or panel manufacturer) starts the process by reviewing a floor plan of the house and deciding upon where to break the walls into panels and specifying panel joints. Together, these determine the panels for the structure. Several commercially-available packages are available to aid in this step: they allow the designer to specify where the breaks are and how to make the joints, following which the corresponding detailed panel designs are generated in a fully or partially-automated manner. The designer considers such aspects as vertical loadings on the structure and preferred panel length in determining where to place the breaks.

Once the panels have been designed, the manner in which they will be stacked is determined. Stacks are typically no more than 12 ft. long (so four stacks will fit into a 50 ft. flatbed truck), 8 ft. deep, and 8 ft. high. The objective in stacking is to minimize the quantity of stacks, subject to (i) each stack either all exterior panels or all interior panels, (ii) all panels face-up in the stack. To satisfy the stated objective, the planner works to squeeze as many panels as possible into each stack layer: a stack orientation of 0° is ordinarily used for panels, but 90° , 180° or 270° are also used as necessary. Exterior panel stacks are formed first, followed by interior panel stacks.

The panels are then produced at the manufacturing facility, using one or more panel production lines. They are made in stack order and in panel order each stack, so that completed panels can be placed directly into their stack at the end of the line. Each panel is marked with a unique identification number on the panel's reference face before being placed in a stack. Because all panels are manufactured and stacked face-up, they can be lowered or lifted and placed directly in the stack: those few panels not at 0° must be rotated to the specified stack angle. At any rate, completed panels can be loaded into stacks by hand and/or using assistive material handling devices (e.g., overhead crane). Once a stack layer is completed, blocking is used as needed to ensure panel layers are stable. If a single production line is used, it is set up to run exterior panels first: these have sheathing and/or thicker framing members so additional processing steps are required. Once exterior stacks are complete, the line is switched over to run interior panel stacks.

One or two days prior to the scheduled construction date, exterior panels are transported to the job site, followed by interior panels. If the floor being built has a garage, stacks are staged off to the side and dropped off one-at-a-time at the garage location (as the garage wall is usually built on-site and thus an opening remains for dropping off stacks throughout the build). Otherwise, multiple stacks (up to 3-4) are dropped off on the structure floor at the same time: additional stacks are staged off to the side as needed. As a result stack drop-off locations, workers may need to carry some panels a substantial distance to get them to their final location in the structure.

Construction workers are provided with a drawing of the panelized structure, but nothing more. They are in general left to their own devices to figure out the sequence in which to install the panels, given the stacks provided. Construction is haphazard at best:

- The panel install sequence favored by the worker is not the sequence the panels are provided in within each stack. More often than not, the panel they want next is not on top of the stack. Workers must then move one or more panels off to the side (usually simply pushed off the stack onto the floor) to get to the panel they want. This results in wasted time and effort in moving/placing such panels, additional time and effort in working around such panels (as they become obstacles), additional safety hazards, and additional time and effort working with temporarily-moved panels (these all required multi-stage panel processing). To avoid these problems, workers sometimes simply work with the most accessible panels in the stack first, resulting in single-stage panel processing but installation difficulties (poor fittability and/or connectivity). This then necessitates additional installation and or fixing and bracing time and effort, as shown by Shewchuk and Guo (2012).
- Workers can have great difficulty in removing panels from the top third or so of the stack, due to the stack height (8 ft.) used. In many cases they have no alternative but to simply knock the panels off the top of the stack, which often results in panel damage (as well as more panels on the floor and in the way).
- Once workers get to the panel they want, they must decide upon how many people are needed for each panel, and which actual workers to use (when more than one individual is available). No guidelines or rules are provided for either process: the workers simply go by their experience. Too few workers and excessive ergonomic risk results; too many and construction is slowed down unnecessarily.
- The self-assigned workers must then figure out how to unload that panel from the stack, get it to the install or temporary storage location (i.e., what path to use) and from what side to install the panel (install vector: Figure 1b). In many cases this is easy to do: in others, however, the best way to unload and handle the panel and best path (or even a clear path around already-installed panels) may not be readily apparent. In the worst case, trapping occurs.
- Once the workers get the panel to the install location, substantial effort is often needed to manipulate the panel into the proper orientation for installation. This is because the panel's starting orientation in the stack has nothing to do with the panel's final location in the structure.

Overall, construction is disorganized, inefficient, and unsafe. Workers often carry panels a considerable distance before installing, frequently having to walk around (or over) other panels lying on the floor or otherwise in the way. Multiple handling of panels is common, as is substantial fixing and bracing (due to lack of fittability and connectivity).

LEAN APPROACH TO PANELIZED RESIDENTIAL CONSTRUCTION

The proposed approach to panelized residential construction is based upon the concepts of lean manufacturing. Pioneered by Toyota beginning in the mid-1950s, lean manufacturing is based upon the core principles of designing jobs with workers in mind, maximizing flow, and doing

things right first time (Monden 2012). A lean approach to panelized residential construction results in the following key concepts:

- Panels are produced in the factory in the order used at the site, not batched into exterior panels and interior panels (lean principles: mixed-model production, setup time reduction).
- At the job site, each panel is processed in one continuous operation (one-piece flow).
- Only the panels in process are out of the stack, with no panels lying around or otherwise in the way. This keeps the work area kept neat and tidy, facilitating panel processing (5S).
- An install sequence is used for panels that maximizes connectivity and fittability, thus ensuring each panel can be installed quickly and correctly the first time (jidoka).
- Panels are stacked, delivered, dropped off at the structure, and processed in a consistent and well-planned manner (standardized work).

Based upon these concepts, panelized residential construction occurs as follows. As before, the lead contractor (or panel manufacturer) reviews the floor plan and selects where to break walls into panels and specifies panel joints. Again he/she uses a commercially-available software package to aid in the process, and considers load points, preferred panel length, and garage location. Additionally, however, he/she then revises the panels based upon downstream planning decisions made as a result of employing the lean approach and proposed methodology (Section 5). This typically consists of making a few panels longer or shorter, and changing some panel joints.

Following panel design, stacks are established. Maximum stack dimensions are again typically 12 ft. length and 8 ft. depth, but height is restricted to 4 ft. The objective in forming stacks is again to minimize the quantity of stacks, but now subject to (i) panels unloadable in a predetermined sequence (*stack unload sequence*), (ii) stack angle = 0° or 180° for every panel. Panels can be either face up or face down in the stack (note that a panel occupies the same volume in a stack layer for any combination of stack angle = 0° or 180° and stack face = up or down, so these decisions do not affect stacking). The stack unload sequence is carefully determined in advance to ensure that (i) a clear path exists for unloading and moving each panel to its destination (install or temporary storage location): no traps occur and squeeze fits are minimal, (ii) successive direct-install panels can be installed one after another, with connectivity between the panels. Note that stacks can be all exterior, all interior, or a mix of both exterior and interior panels, resulting in at most a single partial stack.

The panels are produced at the manufacturing facility using one or more panel production lines. As with the current approach, they are made in stack order and panel order each stack, and are placed directly into their stack at the end of the line. Because stacks can have both exterior and interior panels, however, the lines are now run as *mixed model* lines: an exterior panel can be followed directly by an interior panel and vice-versa. Changeover times between exterior and interior panels must be reduced in order for this to be practical, but this can be done easily using

proven setup time reduction techniques (Monden 2012). At the end of the line, each panel is now marked with both a unique identification number and the panel reference point (Figure 1a). Panels are all manufactured reference face up, but unlike the current approach they may need to be stacked face up or face down, with face down necessitating that the panel be ‘flipped’ before stacking. While this can be done manually, additional material handling equipment can and should be put in place to flip the panels automatically. A rotary table just prior to panel flipping can be used to rotate the panel 180°, if necessary: workers then must simply move the completed panel, already rotated and flipped as needed, to the stack. Because stack layers are not necessarily tight and may even have panels of different thicknesses, considerable blocking may be needed in some cases. Standard blocks, of different lengths, widths, and thicknesses, can be provided at the end of the line in specially-designed storage racks which keep the different blocks separate from one another and easily accessible (5S). This will allow the blocking process to be performed quickly and easily.

Stacks are transported to the job site, staged, and moved to the sub-floor one-at-a-time, as before. Each stack, however, now has a specific drop-off location on the sub-floor, which has been planned in advance to minimize the total weighted panel move distance for that stack subject to all drop-off locations along a single edge of the structure (dropping edge, Figure 1b). The dropping edge is carefully selected in advance to ensure it is (i) accessible, and (ii) results in the best construction process, given that multiple dropping edges are possible. Stack drop-off locations start at one end of the dropping edge and progress towards the other end. With the dropping edge at the bottom of the structure drawing (Figure 1b), stacks will arrive from left to right. Panels are installed in a pre-determined sequence (*panel install sequence*), which starts at the top-left corner of the structure and proceed in a top-down, left-to-right manner, ending (ideally) at the bottom-right corner of the structure (Figure 2a).

Construction workers are provided with a set of *construction plans*. For each stack, they have a drawing which indicates (i) where the stack is supposed to be dropped off, (ii) the stack unload and panel install sequences, (iii) how many workers are to handle each panel, and (iv) the install vector for each panel. The vast majority of panels are direct-install: the remaining panels usually require two-stage panel processing only: temporary storage always consists of leaning the indirect-install panel(s) against a completed wall. In such cases, the wall storage location is shown for each such panel. Construction progresses in a well-defined, orderly, and efficient manner:

- For each stack, the next panel needed is always on the top of the stack. No additional panels need be moved off to the side, onto the floor, etc.
- Because stacks are only 4 ft. high, all panels can be easily removed from the stack.
- The quantity of workers to use for each panel is provided to the workers. In some cases a helper worker is needed for unloading the panel from the stack only: this information is also provided.

- Once the panel is unloaded, the workers must figure out how to get the panel to the install or temporary storage location. A clear, obvious path to the panel's destination will exist in each case.
- Once workers get the panel to its destination, minimal effort is needed to manipulate each panel into the proper orientation for installation or temporary storage. This is because the orientation which minimizes this effort has been determined in advance and used when constructing the stacks at the factory.

Overall, construction proceeds smoothly and efficiently. Panels do not need to be moved far from their stacks, and the path for moving each panel is clear and obvious to the workers. Multiple handling of panels is minimized, as are the amount of fixing and bracing needed (due to maximum fittability and connectivity). Manufacturing and stacking are only slightly more involved, as manufacturing takes little additional time once lean methods in place and additional equipment is available at the end of the production line (as outlined above). Little or no change occurs in stack transport: two 4-ft. stacks take same room as one 8-ft. stack, partial stacks are minimized, and the quantity of stacks remains the same or even decreases (Shewchuk and Guo 2012). Overall, the increased cost of panel manufacturing/stacking is more than offset by the additional time/cost savings and reduced worker lost time, compensation, etc., realized during on-site construction.

METHODOLOGY

The proposed methodology for generating plans for panelized residential construction, using the lean approach, is provided below. Application of the methodology results in (i) a complete set of plans for panelized residential construction of a given structure, and (ii) estimates of performance (stack trips, construction lead time, and ergonomic impact). By varying different parameters at one or more stages, alternative sets of plans are obtained. Designer(s) iterate through the process, generating and comparing alternatives as necessary, until an acceptable set of plans is obtained.

To assist in presenting the methodology, an example (second floor of a 2-story house) will be used. Panelized residential construction for this structure was designed, and the structure built, using the proposed approach and methodology (additional details are provided in the Discussion section).

Step 1: Dropping Edge Establishment

The first step is to establish (i) which of the four edges of the structure (i.e., top, bottom, left, right, as shown on the structure drawing) and (ii) which build directions (left-to-right, right-to-left) are feasible for dropping off stacks. Feasible means that the edge can be accessed with whatever equipment is needed to place stacks along that edge, and there are no other reasons (e.g., road conditions, traffic, etc.) that would eliminate that edge and build direction from consideration.

The remaining steps of the methodology are performed for all feasible combinations of dropping edge and build direction. To facilitate the discussion, it is helpful to consider that in all cases the dropping edge is the bottom edge of the structure on the drawing and the build direction is left-to-right (Figure 2a). This can be obtained for any feasible combination of dropping edge and drop-off direction by rotating the house in the drawing, then mirroring the house along the vertical axis at the center of the house, as required.

Step 2: Stage I Panelization

For each feasible dropping edge/build direction combination, a Stage I panelization plan is developed. Walls are divided into panels, corner joints are established, and panel reference points specified and detailed panel plans developed. This can be done in the traditional manner, except that exterior panel corner joints are established follows:

1. Identify the first and last panels to install, p_{FIRST} and p_{LAST} . This will be the top-left and bottom-right exterior panels, respectively (Figure 2a).
2. Determine two exterior panel build sequences: one going clockwise from p_{FIRST} to p_{LAST} , the other going counterclockwise (Figure 2b)
3. Move from p_{FIRST} to p_{LAST} in each sequence. Whenever a corner joint is encountered and freedom of choice exists, select the joint for which the panel being installed butts against the already-installed panel (Figure 2c), as this is easiest for the workers to install.

Figure 3 shows the Stage I panelization plan for the example structure. Panels 18 and 7 are the first and last panels, respectively: the unnumbered, dashed-line panel represents a double-high first floor panel already installed when the second floor is started. The preferred corner joint could not be used between panels 17 and 16 due to load demands on this joint.

Step 3: Panel Install Sequencing, Determination of Initial Panel Install Vectors

For each feasible dropping edge/build direction combination and Stage I panelization plan, the initial overall panel install sequence and panel install vectors must be established. The objectives are to (i) maximize connectivity and fittability, and (ii) minimize the average distance between final locations of successive panels in the sequence, subject to the install sequence being feasible (all panels reachable, sufficient room to install, workers do not get ‘trapped’ or otherwise boxed in).

In general, these objectives and constraints result in a build pattern where we start at the upper left corner of the structure (first panel), then proceed in a left-to-right, top-down manner, ending at the bottom-right corner of the structure (last panel), as shown in Figure 2a. Exterior panel install vectors are fixed (all panels are installed from the structure floor), interior panel install vectors can be deduced from the install sequence (and rules-of-thumb developed for cases where either install vector, for a given panel, appear equally desirable). Shewchuk and Guo

(2012) present an algorithm for determining the overall panel construction sequence (install sequence) which works well in many cases, but does not guarantee feasible solutions. Investigation of this problem for a wide variety of houses indicates that an algorithm which will provide a feasible solution for all possible cases is extremely difficult, if not impossible, to develop. The aforementioned published algorithm (or a similar algorithm) can be used and the resulting solution modified manually (if required), or the sequence can be generated manually. In either case, a decision-support tool which animates the resulting construction sequence (and shows the install vectors) is beneficial. Note that in any case, the overall panel install sequence generated here is just a starting point: it will be further modified in the following steps.

For the example structure, the initial overall panel install sequence is provided in Figure 4.

Step 4: Stage I Stacking

For each feasible dropping edge/build direction combination, Stage I panelization plan, and overall panel install sequence, we next determine:

- an assignment of panels to stacks.
- stack structures: quantity of layers, panels each layer and location/orientation of each panel each layer. Stack dimensions (length, height, depth) are also established as a result.
- which panels are direct install, which are indirect install.
- where indirect panels are stored (wall locations), how stored (wall panel storage patterns).

This is done via the following steps:

I) Assign panels to stacks, determine initial stack structures.

To make the initial assignment of panels to stacks, we follow Shewchuk and Guo (2012) and divide the initial overall panel install sequence into M non-overlapping sets. Each of these corresponds to a stack. A simple greedy approach can be used: starting with the first panel in the sequence and first stack, assign panels to the current stack, opening up a new stack when needed. Stacks are built one layer at a time, with all panels face-up and having a stack angle of 0° . Layers can be no greater than maximum stack length: a new stack is started if another layer would cause stack height to become greater than maximum stack height. Initial stack unload sequences and stack structures for the example structure are shown in Figure 5.

II) Adjust initial stacks to get rid of fractional stacks, if deemed necessary

A problem which can occur when forming initial stacks is the last stack having only a few layers. To eliminate this partial stack, we can try (i) moving one or more panels to a prior unfilled stack layer, where the panels will fit into the existing 'gap' in the layer, or (ii) moving one or more layers to a prior unfilled stack, where the total height of the layers being moved $\leq$ unfilled stack height. The idea is similar to striving for full work at U-line stations in a lean manufacturing system in order to eliminate fractional workers (Monden 2012).

In either case above, any panels moved must still result in a feasible and acceptable install sequence. In the event that the install sequence becomes infeasible, it may still be possible to salvage it via *additional* panel moves, which in turn must be feasible, etc. The process of determining what panels and/or panel layers to move, and to where, is iterative and ill-defined: it is best accomplished manually using suitable decision-support tools (e.g., software which calculates and outputs new stack structures for a given panel and/or layer move). Furthermore, it must be remembered that eliminating partial stacks in the above manner is not without cost: each time a panel is moved to a different stack location, we move farther away from the initial overall panel install sequence generated in Step 3. Management must decide the extent to which the stacks are to be adjusted.

The initial stacking solution for the example structure (Figure 5) consisted of five stacks, where the last stack had only three single-panel layers. Manual modification of this solution, in the manner outlined above, resulted in a feasible and acceptable 4-stack solution (Figure 6a).

III) Group exterior panels, move to start/end of install sequence, each stack

As a result of how initial stacks are formed, each stack can contain both exterior and interior panels and these can be mixed together. It is desirable to separate the exterior panels in each stack into two groups: those which above the stack clearance area reference line (Figure 2b) and hence far from the stack = $E_{FAR} \in \{p_{FIRST}, \dots, a, b, \dots, d\}$ and those which are at or below this line and hence near the stack = $E_{NEAR} \in \{c, \dots, f, e, \dots, g, p_{LAST}\}$. Panels in E_{FAR} should then ideally be installed first (and thus are found at the top of the stack), followed by all interior panels for the stack, then finally by panels in E_{NEAR} (bottom of stack). This maintains the top-down, left-right build pattern for each stack (originally established via S^*), but has two additional advantages. First, all far and near exterior panels are installed in succession, resulting in economy of setups for exterior panel install. Second, this approach ensures that panels at the top of the stack (most difficult to unload) have the most unload space available, whereas those panels having the least space available for unloading are at the bottom of the stack (easiest to unload). Note that simply putting E_{FAR} first and E_{NEAR} last in each stack is the ideal case: the extent to which this can actually be achieved depends upon whether the desired moves still result in a feasible build sequence.

Applying this concept to the example structure results in panels 14 and 13 (stack 2), 12 and 11 (stack 3), and 9 and 8 (stack 4) moving backwards in the install sequence, i.e., towards the top of the stack. Exterior panels 2 and 3 (stack 2) and 5 and 6 (stack 3) move forwards, i.e., towards the bottom of the stack. Additional stack structure modifications are then performed to stack 3

to bring stack height back down to an acceptable level, resulting in the stacks shown in Figure 6b.

IV) Determine stack drop-off locations

At this point, we have a set of stacks where all panels are assumed direct install: we need to determine where to drop off each stack. The basic approach for establishing drop-off locations for each stack is as follows:

1. *Identify possible stack drop-off locations.* Wherever a stack is dropped off, we consider that some minimum clearance area around the stack will be necessary for workers to walk around the stack, position for unloading panels, and even perform some types of panel unload (e.g., tipping panel directly off of the stack so it rests upright on the floor). This gives rise to the idea of a *stack clearance area* around the stack (Figure 2b). Based upon the stack clearance area and dropping edge geometry, the possible drop-off locations can be established for the stack, using some discrete step size (e.g., 6 inches) along the dropping edge.
2. *Determine feasible drop-off locations, select the best one (and adjust panel locations in stack layers accordingly).* Stack drop-off locations are considered one-at-a-time, moving from right to left along the dropping edge. Each location is feasible if there is no *stack interference* (interference between the stack clearance area and the final location/orientation for all panels in that stack or from a prior stack). If a location is feasible, determine $TWMHC_{STACK \rightarrow INSTALL}(V)$, where V = set of all panels in the stack. In finding this value, we note that whenever we have multiple panels in a stack layer, the panels can be arranged in different ways without affecting the install sequence (e.g., layer contains panels 2 and 5: these could be placed 2,5 or 5,2 in the layer). Thus, for each layer we use the stack layer locations which minimize direct install total weighted material handling cost for the panels in that layer (and revise the stack structure accordingly). If a location is infeasible, the search is stopped. This algorithm locates stacks from left-to-right along the dropping edge (stack #1 is furthest left, followed by stack #2, etc.).

Stack drop-off locations for the example structure, found in the above manner, are shown in Figure 7a.

V) Revise assignment of panels to stacks, stack structures, to ensure dropping edge clear

At any feasible location for stack k , we could have a problem in that we may not have a clear path for dropping off the stack: already-installed dropping edge panels (and immediate successors, if present) from some prior stack $l < k$ could be in the way. When this occurs, we must move those panels to stack k , which then results in a clear drop-off path for stack k as those moved panels can now be unloaded from stack k after it has been dropped off. Such moves can unbalance the stacks, however, or even result in an infeasible solution when

maximum stack height is exceeded for stack k . This problem can be tackled by rebuilding all stacks from k onwards and/or moving other panels from k back to l (while maintaining a feasible overall panel install sequence). In any event, manual intervention is needed to establish what action(s), if any, need be taken.

For the example problem, panel 4 is moved from stack 2→3 and panel 6 from stack 3→4 to ensure the dropping edge is clear for stacks 2 and 3, respectively. To maintain feasible stack structures, panel 12 is then moved from stack 3→2 and panel 10 from stack 4→3 (Figure 7b).

VI) Determine which panels, if any, to store temporarily at walls: establish wall storage locations, wall storage patterns, and revised stack structures and install vectors

As the above procedure for determining stack locations (and adjusting stack structures) progresses through the M stacks, there will be fewer and fewer feasible drop-off locations remaining for each stack. If stack interference occurs with the first (i.e., farthest-right) drop-off location examined, there will be no feasible solutions at all. In this case, the solution is made feasible once again by having the interfering panels (and all immediate successors) at that stack moved to a temporary wall storage location, then installed once the stack is gone. This is done as follows:

1. Determine the set of panels V' going to temporary wall storage: mark these as being indirect-install panels. Let V denote all remaining panels (all direct install).
2. Determine the possible stack layer locations for each panel in V' . Alternatives will exist whenever a multiple-panel layer consists solely of multiple panels from V' , or where multiple panels from V' are found in-between panels from V .
3. Determine the set of possible wall storage patterns (ways in which multiple panels can be 'stacked' against a wall) and wall storage locations to be considered for panels in V' . Then find the set of feasible wall storage pattern/wall storage location combinations, i.e., sufficient room exists for that pattern at that location, along with room for workers in storing and retrieving panels.
4. Find the stack layer locations and feasible wall storage pattern/wall storage location combination which minimizes $TWMHC_{STACK \rightarrow WALL, WALL \rightarrow INSTALL}(V')$.
5. Modify the panel install and unload sequences for that stack to account for temporary wall storage.

The above procedure can also be used when one or more feasible drop-off locations are found prior to an infeasible stack location. When the first infeasible stack location is found, we may decide that it could be used anyways by allowing the infeasible panels to be stored temporarily at a wall. There may be cases where this is quite advantageous, e.g., a location is infeasible due to a single interfering panel, but total weighted material handling cost can be improved significantly if that location is used. This is a management decision: the choice depends upon

not only the specifics of the particular case but also upon what company feels is more important: reduced material handling or reduced two-stage panel processing.

For the example problem, stack interference does in fact occur with the first (farthest right) drop-off location for stack 4. The stack clearance area and resulting panels exhibiting stack interference (panels 35, 36, 37, 38, 40, 41, 42, 43, and 52) are shown in Figure 8a. This problem was particularly difficult in that one panel required two temporary wall storage areas in order for a feasible solution to be possible. Figure 8c shows the original panel install sequence (stack unload sequence) and panel install sequence generated considering stack interference: the subsequence of panels exhibiting stack interference is 52-35-42-36-37-38-40-41-43. As these panels must be installed in this sequence, they must go to wall storage in the reverse sequence, i.e., 43-41-40-38-37-36-42-35-52. The last panel in this sequence does not need to go to temporary wall storage, however, as once it is taken the stack is gone so it can go directly to the install location. This results in the stack unload sequence shown in Figure 8c, where all indirect-install panels are taken to wall storage location #1 (Figure 8b). From this location, all panels go to their final location except panel 41, which goes to wall storage location #2. Once the last remaining panel at wall location #1 (panel 43) has been installed, panel 41 can be taken from wall location #2 to its final location.

VII) Perform final modifications to stack structures

Once temporary storage has been established, a final check is made of all stacks and final adjustments are made as desired. For the example structure, these result in the final stack structures shown in Figure 9.

Step 5: Stage II Panelization

Once Stage I stacking has been completed, the panel install sequence, panel install vectors, and stack (and temporary wall storage, if used) locations are all known. Based upon this information, the preferred corner joints for interior panels can be determined. Considering the example problem, we have the partial install sequence 36-37-38, where these panels all come from wall storage location #1 (Figure 8). With the initial specification of these panels (Figure 3), panel 37 must be moved 'behind' the far end of panel 36 in order to install: installation is easier if the corner joint is 'flipped' (Figure 2c). The entire Stage I panelization plan is examined and interior corner joints are flipped as appropriate. Note that whenever a corner joint is flipped, one panel becomes longer and another shorter. A check must be made to ensure that maximum panel length is not violated for any panels: if this occurs, we backtrack to Stage I panelization and modify panels as required.

For the example problem, interior panel pairs for which corner joints are flipped are (36,37), (46,47), (54,55), and (11,12): all panel lengths remain feasible.

Step 6: Stage II Stacking

Whenever a corner joint is flipped in Step 5 and one panel becomes shorter and the other longer, the stack layers containing such panels can also become shorter and longer. If maximum stack length is exceeded for any stack, the stack becomes infeasible. A check is made on all affected layers of each stack: if any such layer is found to exceed maximum stack length, the stack is rebuilt. In the event that this causes maximum stack height to be exceeded, panels must be moved between stack layers until a feasible solution is found, which may necessitate additional changes to stack structures, etc. In other words, iteration is then required starting with Step 4. For the example problem, all stacks remained feasible (no changes were required).

Step 7: Construction Planning

At this stage, the only construction planning remaining is to determine how many workers work with each panel. A key assumption here is that the set of workers assigned to a panel at the start of a process (unload→install, unload→wall, or wall→install) remains constant. While workers sometimes do jump in to provide extra assistance, field studies and observations indicate that our assumption is valid the majority of the time. Given this method of operation, the quantity of workers must be established once for each panel/process. A simple approach is used here: the quantity is based solely upon cut-offs which specify worker quantity as a function of panel weight and size. These cut-off values are specified by the user (e.g., contractor).

Step 8: Panel Orientations in Stacks, Stack Drop-off Times, Performance Estimation

At this stage we have a feasible set of panelization plans, stacking plans, stack transport plans, and construction plans. Recall that all panels are face-up in the stack, with a stack angle of 0° (from Step 4). In many cases, however, it may be much easier for the workers to unload and manipulate a panel into the proper orientation for installation (or temporary storage) if the stack angle is changed to 180° and/or the panel is placed face-down in the stack (note that such changes have no effect on panel locations in stacks or stack dimensions). Considering our example (see Figures 3 and 7a), panel 1 can be flipped off the stack reference edge (Figure 1) to an upright position resting on the ground: at that point it is in the exact orientation needed for installation. Consider next panel 18: keeping this panel face-up and at 0° in the stack means that the panel will need to be rotated 180° on top of the stack before flipping off, then rotated another 180° in the xy plane once upright, in order to get into the proper orientation for installation. Thus, at this stage we determine, for each panel, stack face and angle which minimizes the effort needed to unload and manipulate each panel, then revise the stack structures accordingly.

To solve this problem, simulation is used. A discrete-event simulator of the panelized residential construction process, as described in this paper, has been developed. Encompassed within the simulator are detailed models of the various activities workers can employ to unload, carry, move, and install panels, along with specifications of the conditions

under which each activity can be used and methods for establishing the effort (and ergonomic risk) associated with each activity. Given a panel in a stack with a specified stack face and stack angle, the simulator can establish the best way to unload, carry, and install the panel (detailed description of the simulation is beyond the scope of this paper). Using simulation, a novel approach to solving the problem can be used. The construction process is simulated, using the plans established at this point (i.e., all panels face-up, stack angle = 0°) and the crew size specified by the user. Following simulation, the final orientation of each panel is examined. If the panel orientation is correct, the initial stack face and stack angle were correct. If, on the other hand, the panel is upside-down and/or the reference face is facing the wrong direction, stack face and/or stack angle must be modified: the exact changes needed can be deduced directly from final panel orientation following simulation.

As the above activity simulates the entire construction process, the simulation can also be used to provide estimates, for a given crew size, of stack drop-off times, construction lead time and overall ergonomic load on the workers. Snapshots of a simulation animation for the example structure are shown in Figure 10. Further details on how ergonomic risks are calculated based upon simulation run data are beyond the scope of this paper.

DISCUSSION

Examples of the panelization plans, stacking plans, stack transport plans, and construction plans for the example structure of the previous section are shown in Figures 11-14, respectively. As previously mentioned, the example structure constituted the second floor of a 2-story house: a similar set of plans were generated using the proposed approach and methodology for the first floor. The entire panelized house was then planned and built, per the lean plans, by a commercial construction firm in February 2015 in northern Virginia. The panel construction and stacking procedures in the factory were observed, and the entire construction process videotaped, for both floors of the structure: workers were also interviewed following construction. Due to equipment limitations and manpower constraints at the factory, the stacking plans provided could not be followed one-hundred percent: two changes were made. The first of these is that panels could not be flipped to be loaded onto their stack face-down: all panels were thus face-up regardless of what was specified in the stacking plans. The second is that in several instances when constructing stacks, a panel was moved to a different location within its stack to better utilize empty space (thus changing the planned panel removal and install sequences).

To provide a reference for comparison, the construction of a nearly-identical second house (first floor identical, second floor about 90% identical), using the traditional approach, was similarly studied and documented. This house was built by the same construction firm in March 2015, using a similar worker pool and the same quantity of workers for each floor (7 for the first floor, 6 for the second) as in the lean house. The completed houses are compared, on a floor-by-floor basis, in terms of both productivity and workload measures. Productivity is established via stack quantity and construction lead time, while workload is established via connectivity, fittability, and average panel handling steps. Connectivity and fittability were introduced in the Modeling

Framework section: the third measure introduced in that section (total weighted panel material handling distance) could not be used due to the difficulty in determining actual panel move distances from videotape analysis. A substitute measure more conducive to video analysis, panel handling steps, was used instead. This refers to the sum of how many times a panel was lifted (and processed continuously before putting down again), erected (moved to an upright position for installation), and flipped (reoriented in order to be installed properly).

Results are presented, both floor-by-floor and on an overall basis, in Table 1. Overall results show that the lean approach led to improved productivity, with 26% fewer stacks to deliver and a 12% reduction in construction lead time. Additionally, the lean example was characterized by reduced workload: connectivity and fittability were increased by 13% and 22%, respectively, while average panel handling steps was reduced by 26%. While these improvements are deemed significant, it should be noted that several factors biased the results against the lean approach:

- stacking plans for the lean home were not followed 100%. Some panel orientations in stacks were incorrect, which would necessitate additional panel manipulation prior to install. Stack structures were modified in some cases: the resulting modifications to stack unload and install sequences, as previously discussed, can result in additional temporary panel storage and increased panel move distance.
- construction plans for the lean home were not followed 100%. Table 1 indicates the planned connectivity and fittability for each floor with the lean approach: connectivity is always 100% in the lean approach and fittability 100% or nearly so. Because the plans were not followed completely, actual connectivity and fittability were lower than planned and the improvement for these measures was only about half of what was possible.
- the overall work pace for the lean home was observed to be slower than that for the traditional home. This was due to the fact that the workers were unfamiliar with the lean approach and hence undergoing a learning curve.
- while only one stack was on the floor at a time in the lean approach (by design), multiple stacks were on the floor at the same time in the traditional home. As a result, workers in the traditional home were able to process multiple panels simultaneously and were often installing 2-3 panels at the same time. This parallel processing caused an increase in processing speed (likely significant) for the traditional home. The effect appeared most pronounced for the second floor (which showed the smallest improvement in construction lead time).

Considering all of these factors together, the performance improvements shown by the case study comparison are likely a substantial underestimation of the potential of the proposed approach and methodology to improve panelized residential construction. Regarding the actual construction process, video review and worker interviews indicated the following:

- the workplace was more structured, better-controlled, and appeared safer with the lean approach. Workers really liked the fact that they knew exactly which panel to take next and where to take it. They also thought the process to be more efficient and liked the

fact that they didn't need to shuffle through panels in a stack to find the next one to install. Overall, they appeared happy with and preferred the lean approach.

- the workplace appeared much less safe using the traditional approach. More panels were lying on the floor, and multiple panels were sometimes moved simultaneously at a fast pace, increasing the likelihood of collisions or other accidents. Additionally, because there was insufficient space to work with the panels, workers were often seen working much closer to the edge of the structure, increasing risk of falling of the structure edge.

Overall, construction appeared to proceed more smoothly, and with less congestion and chance of accidents, when the lean approach was employed. It is important to note that these benefits were obtained simultaneously with reduced workload and improved productivity, as described above. In practice, reductions in construction lead time typically occur at the expense of reduced worker safety and/or increased workload, but no such trade-offs occurred here.

CONCLUSIONS

In this paper, a lean approach and methodology for panelized residential construction was presented. The approach and methodology are comprehensive, covering everything from panel design and manufacture through to panel stack delivery and construction planning. The items were applied to a real house: plans were generated and the house built, as much as possible, according to the plans. A second house, with a nearly-identical floor plan, was designed, planned and constructed using the traditional approach to panelized residential construction, and performance compared across the two structures. The comparison showed that the lean house required fewer panel stacks, was built faster, and provided a cleaner, safer work environment with reduced workload (improved ergonomics) as compared to the traditional home: measure-specific improvements ranged from 12-26%. These magnitudes of improvement underestimate those which are possible in general with the proposed approach and methodology, however, due to some implementation difficulties (plans not followed exactly) in the factory and at the construction site, and worker unfamiliarity with the lean construction process. The comparison also indicated that the lean approach and methodology can simultaneously improve productivity, worker safety, and workload: trade-offs between these factors need not occur.

While the single case study example illustrates the potential of the proposed approach and methodology, further comparative field study experiments are necessary to more concretely establish the expected level of improvement. Additionally, given a suitable simulation-based decision-support system for implementing the lean approach, computer experiments can be performed to try determine the best way to design and plan for panelized residential construction. For example, when are many small panels preferable to fewer large panels? Are a few large stacks better than a larger quantity of smaller stacks? And when is it preferable to have one stack in process at a time (less congestion, more room to work) as opposed to several (more opportunities for multiple panels in-process at the same time)? Efforts are underway to answer these questions: such information would help guide companies in establishing how they

will perform panelized residential construction, whether the proposed approach and methodology are followed in detail or not.

Further work is also needed to establish how detailed ergonomic assessments of workers performing panelized residential construction can be made. Work is underway to integrate such assessment procedures with discrete simulation of the panelized residential construction process: the simulation generates and outputs worker and panel position/movement data and an 'ergonomics assessment engine' post-processes the information to establish ergonomic assessment measures for the workers. Such information would provide a much more detailed and accurate picture of how workers are impacted than the simple surrogate workload measures employed in the case study investigation in this paper.

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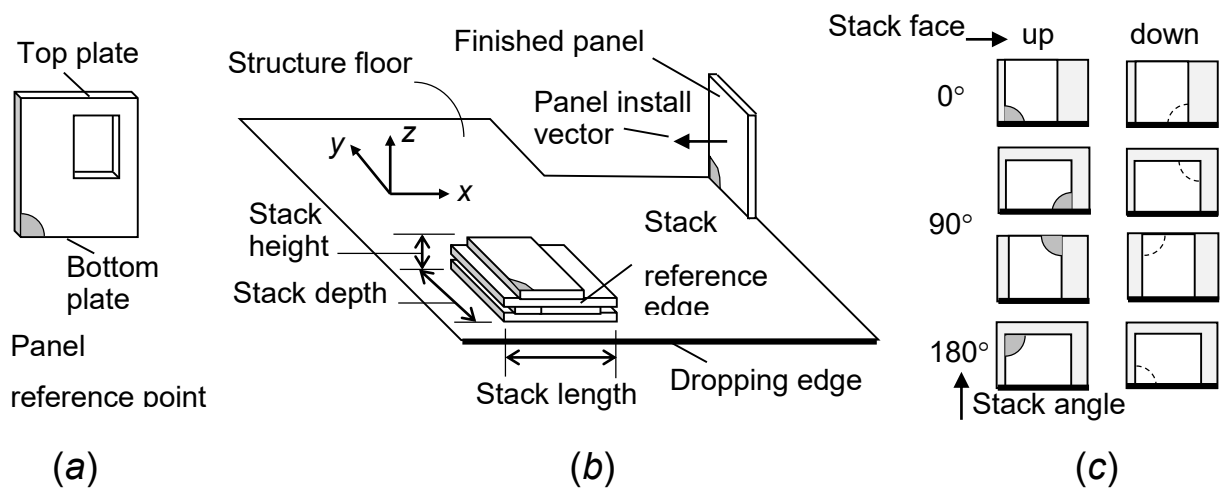


Figure 1. Terminology used to describe panelized residential construction process: (a) panels, (b) structure floor, stacks, installed panels, (c) panel orientations in stacks.

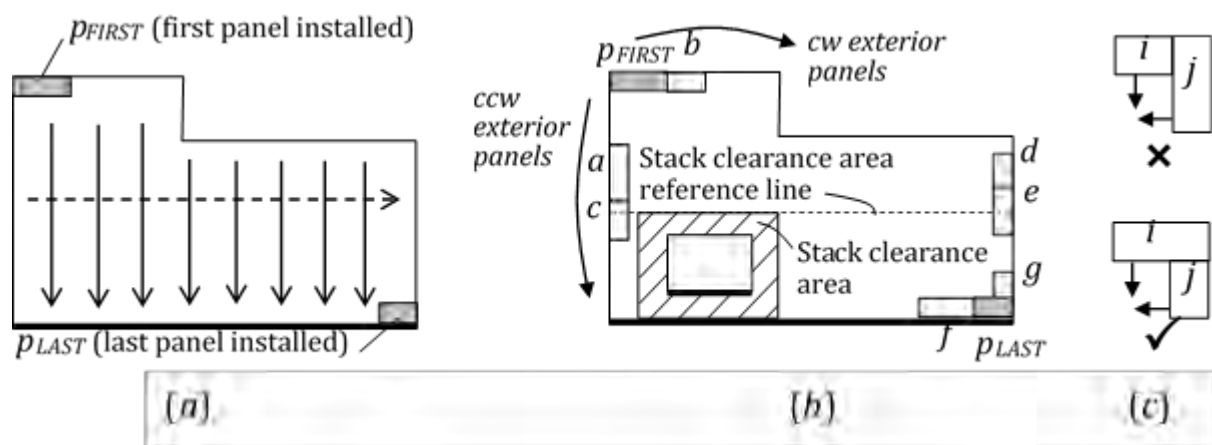


Figure 2. (a) Overall top-down, left-to-right panel install pattern, (b) cw and ccw exterior panel build sequences, (c) Exterior panel corner joint alternatives when panel j follows i .

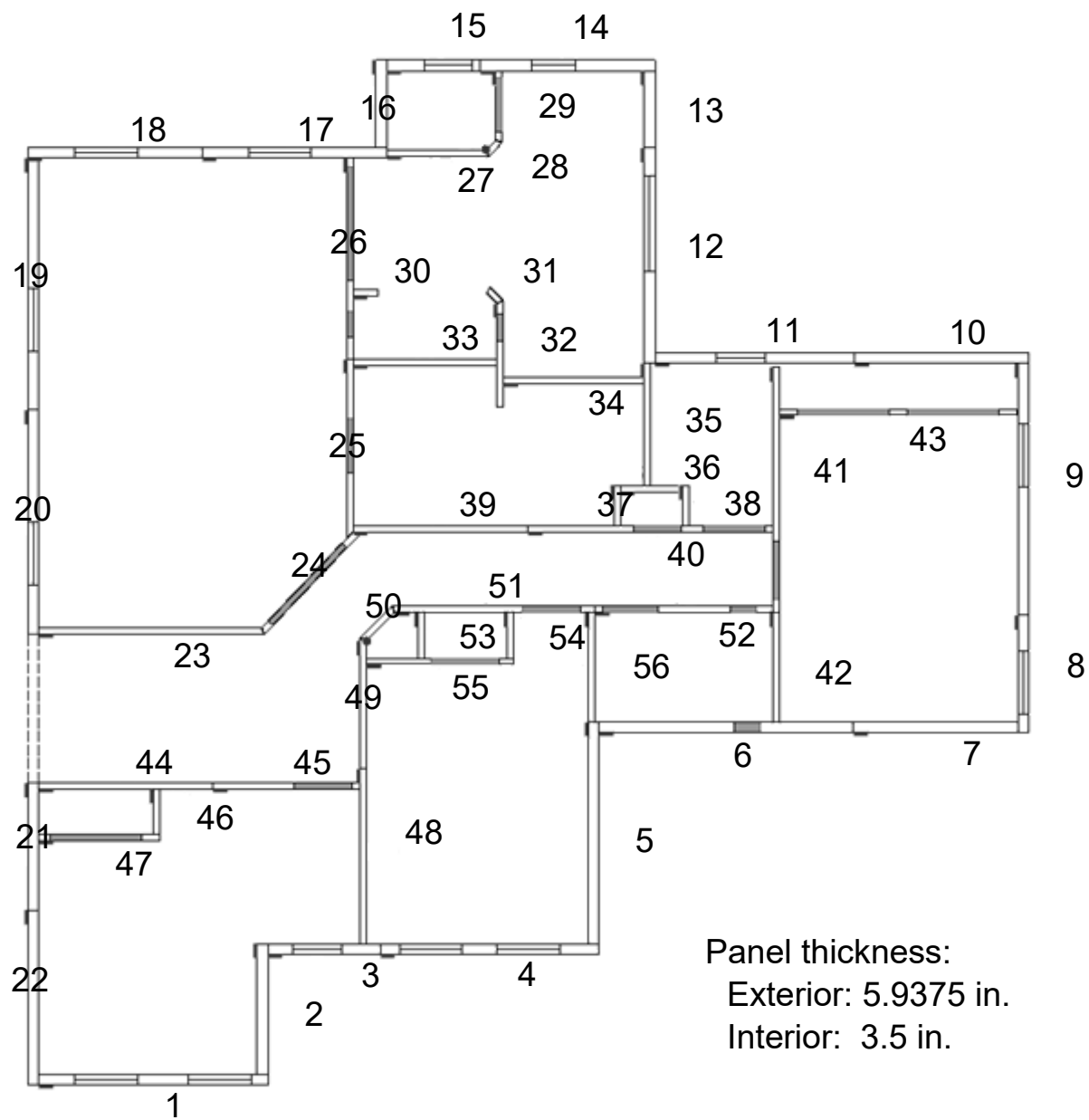


Figure 3. Stage I panelization plan for example structure.

Npanels:
56

Ideal panel install sequence:

18	19	17	20	21	22	1	2	3	23	44	46	47	16	15	14	4	26	25	45
48	49	29	27	28	30	33	32	31	13	12	5	6	34	39	24	55	53	54	56
51	50	11	35	36	37	38	40	52	41	42	10	9	8	43	7				

Figure 4. Initial overall panel install sequence for example structure.

Panels and layers each stack, unload sequence (LSmax=144, HSmax=48)

S1 (47.5): 18 19 17 20 21 22 1 [2 3]
S2 (45.8): 23 44 [46 47][16 15] 14 4 26 25 45 48 [49 29]
S3 (44.8): 27 [28 30 33][32 31 13] 12 5 6 34 39 24 [55 53 54]
S4 (45.8): 56 51 [50 11] 35 [36 37 38] 40 52 41 42 10 9
S5 (15.4): 8 43 7

	i	-panels-	-panel	lengths-		i	-panels-	-panel	lengths-
S1	18		96.00		S3	27		56.00	
	19		138.50			28 30 33	10.63	13.50	79.00
	17		101.50			32 31 13	57.00	10.63	42.50
	20		123.50			12		118.50	
	21		70.00			5		122.00	
	22		96.44			6		140.06	
	1		126.06			34		77.50	
	2 3		72.00	62.06		39		96.00	
						24		78.50	
S2	23		122.81			55 53 54	81.00	25.00	25.00
	44		96.00						
	46 47		25.00	66.50	S4	56		60.00	
	16 15		48.00	51.50		51		111.50	
	14		96.00			50 11	24.75	109.75	
	4		120.00			35		67.00	
	26		110.50			36 37 38	34.00	22.00	22.00
	25		98.88			40		135.00	
	45		81.00			52		98.13	
	48		96.00			41		135.00	
	49 29		72.00	39.50		42		60.00	
						10		96.00	
						9		138.50	
					S5	8		64.44	
						43		130.50	
						7		90.69	

Figure 5. Initial stack structures for example structure.

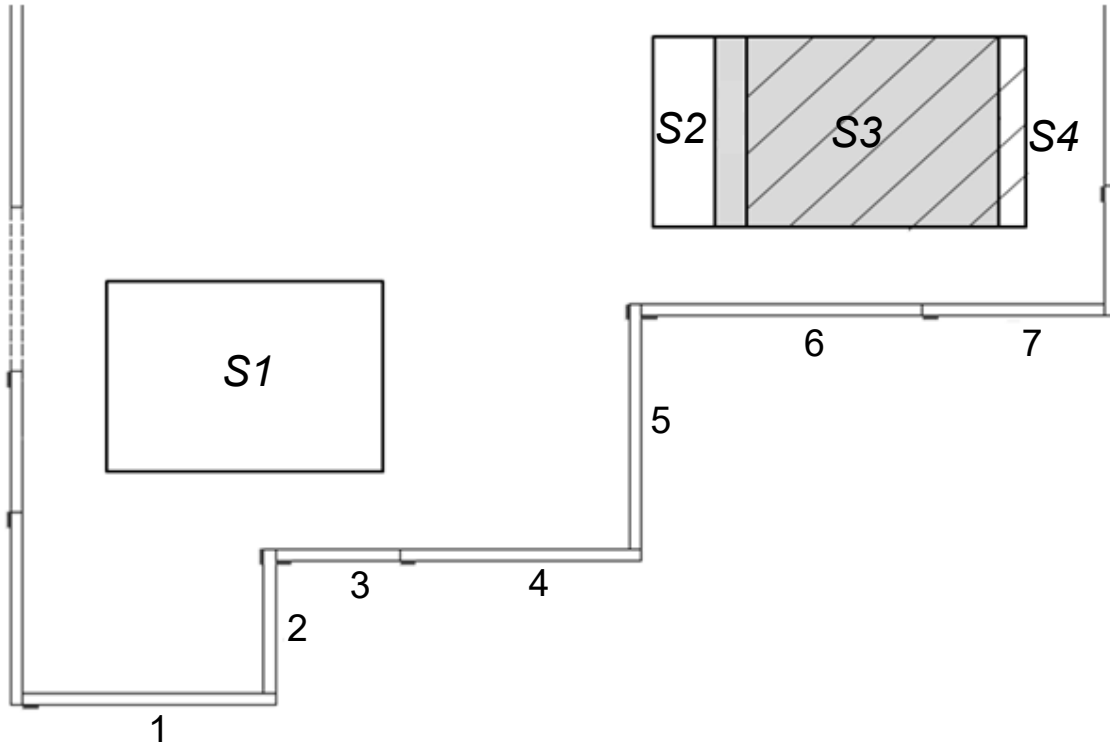
S1 (47.5): 18 19 17 [16 15] 20 21 22 1
 S2 (45.8): [2 3][47 27][46 44] 23 [14 13] 4 26 25 45 48 [49 29 30 28]
 S3 (44.8): [33 32][31 12] 5 6 [34 56] 39 24 [55 53][54 51][50 11]
 S4 (44.8): [42 35][36 37 38] 40 52 41 10 9 8 43 7

(a)

S1 (47.5): 18 19 17 [16 15] 20 21 22 1
 S2 (45.8): [14 13][47 27][46 44] 23 26 25 45 [2 3] 4 48 [49 29 30 28]
 S3 (44.8): 12 11 [33 22][31 55 53 54] 5 6 [34 56] 39 24 [51 50]
 S4 (45.8): 10 9 8 [42 35][36 37 38] 40 52 41 43 7

(b)

Figure 6.(a) Stack structures modified to eliminate fractional stack, and (b) exterior panels moved forwards and backwards for each stack, stacks adjusted, example structure.



(a)

S1 (47.5): 18 19 17 [16 15] 20 21 22 1

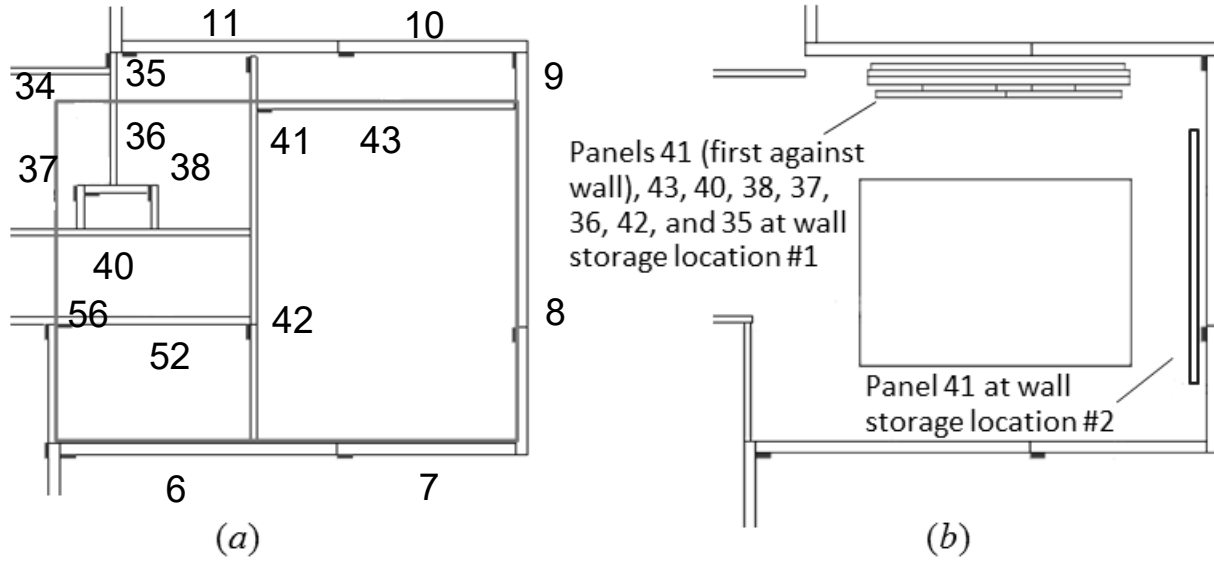
S2 (45.8): [14 13] 12 [47 27][46 44] 23 26 25 45[2 3] 48[49 29 30 28]

S3 (44.8): 11 10 [33 22] 4 5 [31 55 53 54][34 56] 39 24 [51 50]

S4 (44.8): 9 8 [42 35][36 37 38] 40 52 41 43 6 7

(b)

Figure 7. (a) Stack drop-off locations and (b) stack adjustments for clearing dropping edge, example structure.



S4 (44.8):	9	8	[42*	35*]	[36*	37*	38*]	40*	52*	41*	43*
6	7										
Install seq:	9	8	6	7	52*	35*	42*	36*	37*	38*	40*
41*	43*										
Unload seq:	9	43 ¹	41 ¹	40 ¹	[38 ¹	37 ¹	36 ¹]	[42 ¹	35 ¹]	8	6
7	52										
From wall #1:		35	42	36	37	38	40	41 ²	43		
From wall #2:		41									

* = stack interference

1 = indirect install, take to wall location #1

2 = indirect install, take to wall location #2

(c)

Figure 8. (a) Stack clearance area for last stack, showing panels exhibiting stack interference, (b) wall storage locations for last stack, and (c) modification of last stack (use of temporary wall storage) to deal with stack interference, example structure.

S1 (47.5): 18 19 17 [16 15] 20 21 22 1

S2 (45.8): [14 13] 12 11 10 2 3 [47 27][46 44] 23 26 [25 30]

S3 (43.4): [29 28 33][45 32] 4 5 48 59 [31 55 53 54][34 56] 51 [50 39] 24

S4 (44.8): 9 43 41 40 [38 37 36][42 35] 8 6 7 52

Figure 9. Final modification and adjustment to stacks, example structure.

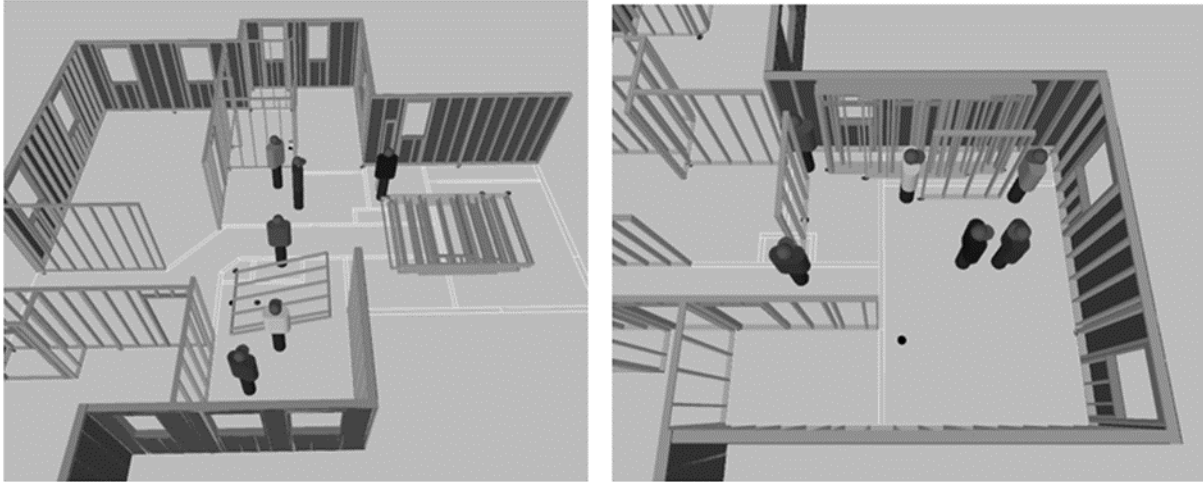


Figure 10. Snapshots of simulation animation of example structure.

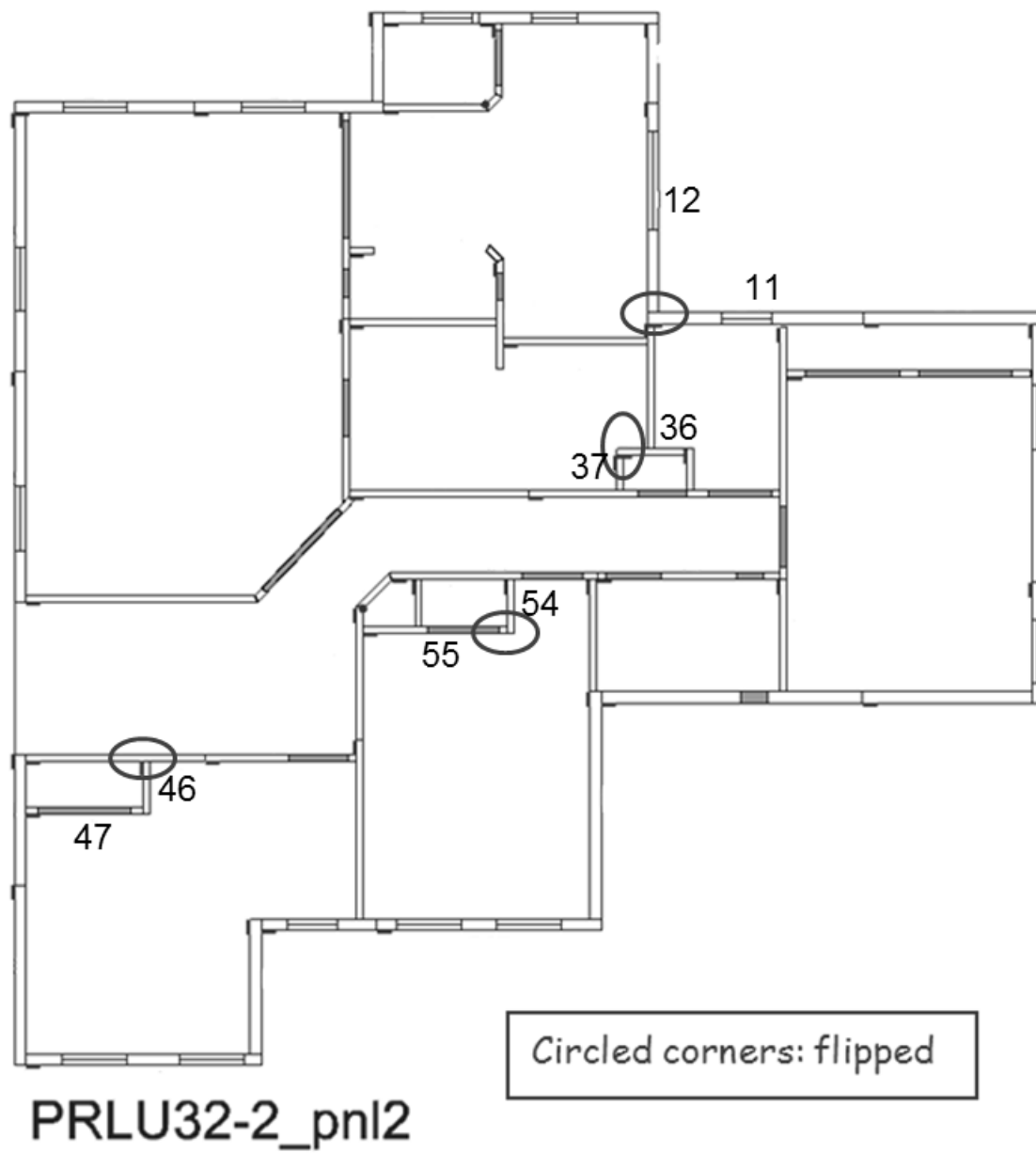
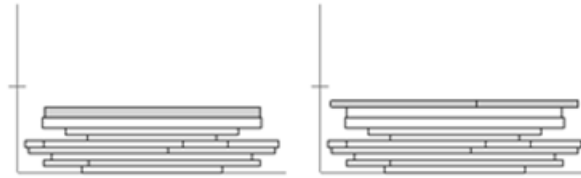


Figure 11. Panelization plan for example structure.

PRLU32-2

Stack 3
Layers 9-10



29 28 33

45 32

4

5

48

49

31 55 53 54

34 56

51

50 39

24

Layer
9

B37



Layer
10

36, 23

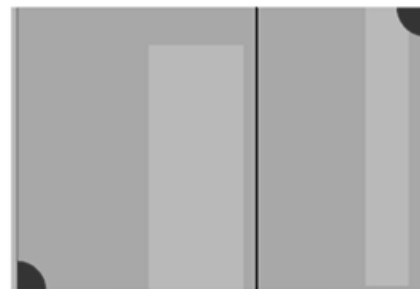


Figure 12. Example of stacking plans for example structure.

PRLU32-2 Stack 3 Drop-Off Details

Drop-off time: 6724

Length: 11-9-10

Height: 3-7-6

Stack panels:

29 28 33

45 32

4

5

48

49

31 55 53 54

34 56

51

50 39

24

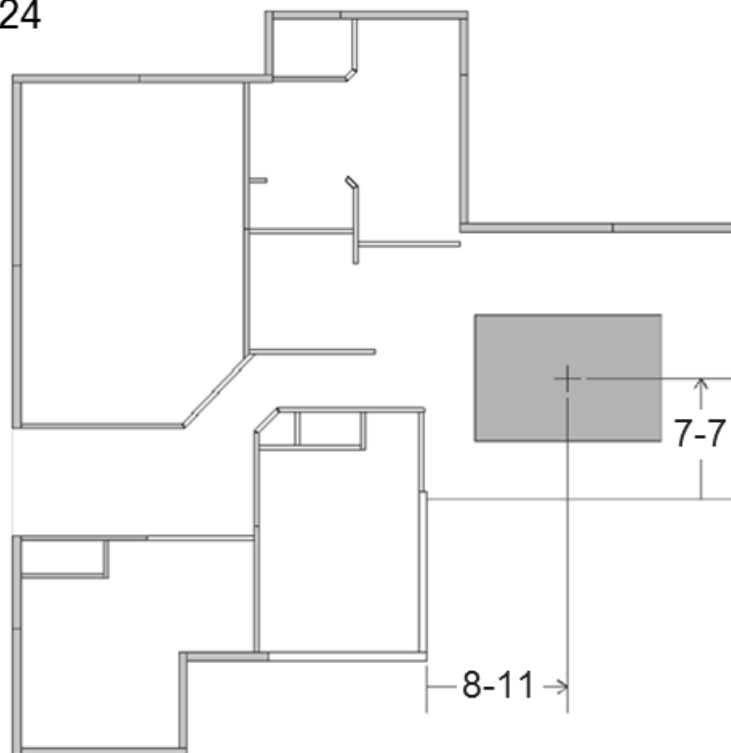


Figure 13. Example of stack transport plans for example structure.

PRLU32-2 **Stack 4 Panel Build Sequence From Stack**

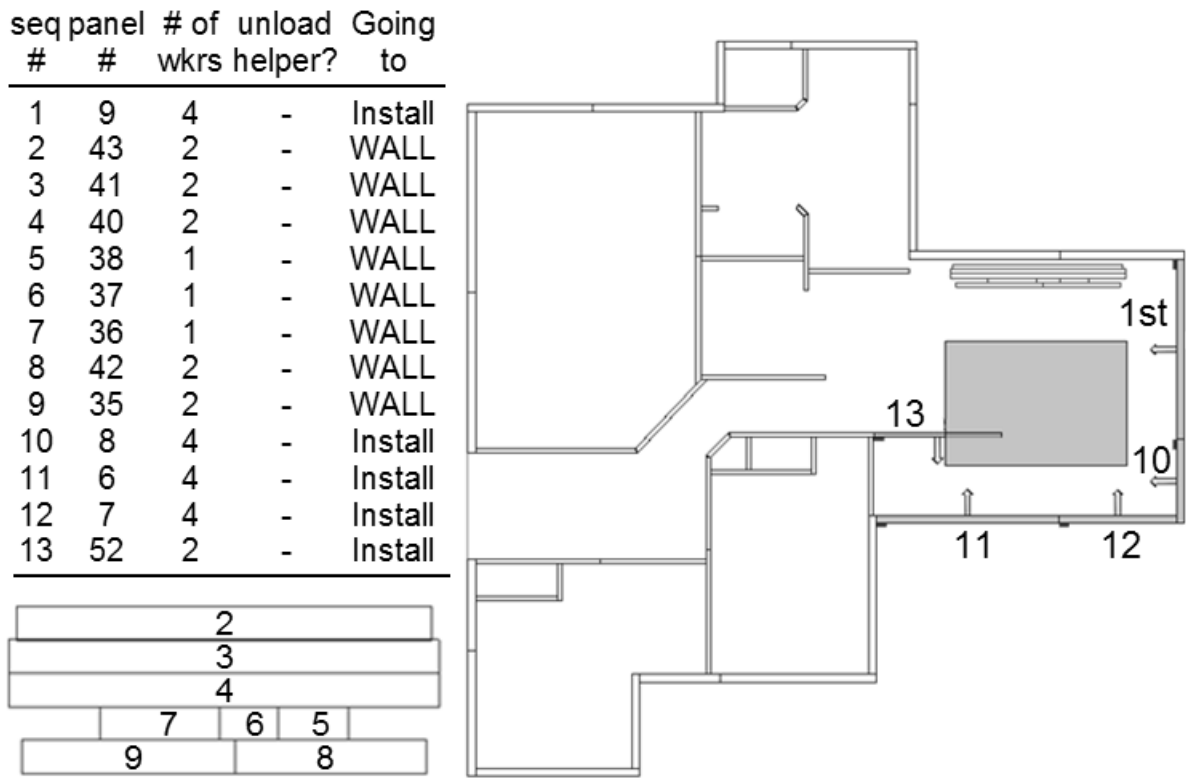


Figure 14. Example of construction plans for example structure.

Table 1. Performance comparison of lean vs. traditional approach, example structure.

Performance Measure	Structure and Approach						Overall % improvement (average over both floors)
	1st Floor			2nd Floor			
	Lean	Traditional	% Improvement	Lean	Traditional	% Improvement	
Stack quantity	4	5	20	4	6	33	26
Construction lead time	80 min.	103 min.	22	106 min.	108 min.	2	12
Connectivity, actual (planned)	94% (100%)	84%	12 (19)	100% (100%)	88%	14 (14)	13 (17)
Fittability, actual (planned)	87% (98%)	75%	16 (31)	91% (100%)	71%	28 (55)	22 (43)
Average panel handling steps	3.7	4	8	2.8	6	33	26

5. Methods for Field Exposures of Ergonomic Risks

4.1. Wearable technologies for field-based ergonomic assessments

Kim S, Nussbaum MA: [2013] Performance evaluation of a wearable inertial motion capture system for capturing physical exposures during manual material handling tasks. *Ergonomics* 56:314-326.

Abstract

With a long-term goal of improving quantification of physical exposures in the workplace, this study examined the ability of a commercially-available inertial motion capture (IMC) system in quantifying exposures during five different simulated manual material handling tasks. Fourteen participants repeated all these tasks in three 20 min. sequential time blocks. Performance of the IMC system was compared against an optical motion capture (OMC) system (“gold standard”) in terms of joint angles, angular velocities, and moments at selected body parts. Though several significant changes in performance over time were found, the magnitudes of these were relatively small and may have limited practical relevance. The IMC system yielded peak kinematic values that differed by up to 28% from the OMC system. The IMC system, in some cases, incorrectly reflected the actual extremity positions of a participant, and which can cause relatively large errors in joint moment estimation. Given the potential limitations, practical recommendations are offered and discussed.

1. Introduction

Enhancing the quantification of physical exposures (e.g., joint kinematics and kinetics) in the workplace has been argued as a growing need (Garg & Kapellusch 2009; Marras *et al.* 2009; Waters *et al.* 2007) . Ideally, such quantification should be *in situ*, since the work environment (e.g., physical constraints, workplace culture, etc.) can influence the specific work strategies adopted, and which in turn can affect the level of estimated physical exposures (Cutti *et al.* 2007; Garg & Kapellusch 2009; Marras *et al.* 2009; Waters *et al.* 2007; Wells *et al.* 2004). This potential influence, along with evidence that the temporal variation of physical exposures is likely related to injury risk (Wells *et al.* 2007; Westgaard & Winkel 1996), argues for the importance of being able to quantify physical exposures in the workplace.

Occupational physical exposures have been quantified in numerous existing studies. Such quantification typically involves some combination of kinematics and kinetics, often supplemented or substituted by physiological (e.g., muscle activity or heart rate) and subjective (e.g., discomfort or exertion) measures. Less commonly, loads acting internally (i.e., to specific body tissues such as intervertebral joint) are estimated using biomechanical models. Mature technology exists to capture body kinematics (e.g., optoelectronic motion capture systems, OMC) and external kinetics (e.g., force platforms), though these are somewhat non-portable and could be restrictive of worker behaviors. Such limitations likely explain why relatively few studies (Faber *et al.* 2008; Marras *et al.* 1993; Morlock *et al.* 2000; Norman *et al.* 1998) have obtained detailed kinematics and/or kinetics *in situ*.

Recent advances in wearable measurement systems, such as inertial motion capture (IMC) systems, may facilitate monitoring of body kinematics in diverse work environments. The potential application of an IMC system, or more specifically its primary component — an inertial measurement unit (IMU) — has been widely explored in recent years, primarily in more basic, clinical, and sports-related research. For example, IMUs have demonstrated potential as an alternative tool for clinical evaluation to assess joint kinematics of the upper extremity (Cutti *et al.* 2007; de Vries *et al.* 2010; Luinge *et al.* 2007), the lower extremity (Cloete & Scheffer 2008; Favre *et al.* 2008; Picerno *et al.* 2008), and the spine/trunk (Giansanti *et al.* 2007; Goodvin *et al.* 2006). In such studies, however, IMUs exhibited measurement errors in orientation that depended on motion characteristics (e.g., direction and speed of motions), and were generally tested over short time periods. This raises concerns regarding application to occupational physical exposure assessment, particularly since occupational tasks involve varying motion directions, ranges, and speeds. Further, many occupational tasks (in distribution centers, hospitals, and construction sites, as examples) are often non-routinized, so that a prolonged observation can be required to describe exposure variability (Gold *et al.* 2006; Paquet *et al.* 2005). Though there are other prototype wearable systems [e.g., a hybrid system for the 3D measurement of trunk motion using IMUs (Plamondon *et al.*, 2007)], our current interest is in the application of an IMC to occupational manual materials handling (MMH) tasks, which are a well-documented risk factor for work-related musculoskeletal disorders (NRC & the Institute of Medicine 2001). To the authors' knowledge, however, use of an IMC for such tasks has yet to be evaluated.

This study thus aimed to assess the ability of an IMC system to quantify physical exposures for several MMH tasks over a relatively prolonged period of time. To achieve this, MMH tasks were simulated in a laboratory environment. Such an environment was required so that IMC measures had a basis of comparison. Here, an OMC was used, which is generally viewed as the “gold” standard for kinematic measurement (in a laboratory). Comparisons were hence made of physical exposure measures (joint angles, angular velocities, and moments of selected body parts) obtained using an OMC vs. a commercially available IMC system. Results of this study were intended thereby to contribute to the development of future investigations of MMH tasks using an IMC system.

2. Methods

A convenience sample of 14 participants (11 males and 3 females) was recruited from the local community; means (SD: Range) of age, stature, and body mass were 22.9 (4.9: 19 - 38) yrs, 172.4 (8.9: 157 - 185) cm, and 72.8 (9.5: 54 - 86) kg, respectively. All participants reported being physically active and with no musculoskeletal disorders within the past year. Informed consent was provided using procedures approved by the Virginia Tech Institutional Review Board.

2.1 Experimental design

For the purpose of assessment, five simulated MMH tasks were completed by participants in a laboratory setting, and these tasks were intended to represent a range of occupational demands. All tasks were performed using an 18 kg box (width x length x depth = 33 x 48.3 x 24 cm). This mass is near the median of values handled by the U.S. workforce (Ciriello *et al.* 1999). The specific MMH *Tasks* were (Figure 1):

- 1) Symmetric lifting and lowering, to/from ground height (LL_{GROUND}). Participants lifted the box from the ground to individual elbow height, paused briefly (~2 sec), and lowered the box back to the ground.
- 2) Symmetric lifting and lowering, to/from knuckle height ($LL_{KNUCKLE}$). As above, but beginning and ending the task at individual knuckle height.
- 3) Asymmetrical lifting and lowering (LL_{ASYM}). Participants transferred the box from one table to another. The tables were located at each side of the participant at a horizontal distance of about 65 cm from the centerline of a body.
- 4) Carrying (Carrying). Participants carried the box for 2 m, roughly the median value in the US workplace (Ciriello *et al.* 1999).
- 5) Pushing/Pulling (PushPull). Participants symmetrically pushed (pulled) the box away from (toward) the body a distance of 70 cm, with the table adjusted to individual knuckle height and the box located in front of the participant.

Three trials of each MMH task were completed, and each began with participants standing with each foot on a separate force platform, in an upright stance, with the arms hanging relaxed, and the feet hip-width apart. All tasks were performed in a freestyle manner that was self-selected as comfortable for a given task, and which was considered a more realistic representation of actual workplace behaviors. To determine if the performance of the IMC system (see below) changes over time (e.g., due to “drift”), all tasks were completed in three 20 min. *Time Blocks*. Each block consisted of 15 trials (3 repetitions x 5 MMH tasks), and 10 min of rest was provided between each block. During the intervals between trials and during 10-min rest periods, participants were asked to relax and behave naturally but to stay on the 5.2 × 5.5 m wooden platform (the experimental area, in which there were no significant ferromagnetic influences). The presentation order of *Task* was partially counterbalanced, and the order was held constant for a given participant in each time block.

Figure 1. Illustration of experimental tasks.

2.2 Instrumentation

Bilateral ground reaction forces and moments were collected using the two force platforms (AMTI OR6-7-1000; AMTI, Watertown, MA, USA), and tri-axial hand forces were collected using

two load cells (AMTI MC3A-6) that were attached at the lateral faces of the box as handles (Figure 1). Force platform and load cell signals were sampled at 960 Hz, then low-pass filtered (15 Hz cut-off; second order Butterworth; bidirectional) and down-sampled to 60 Hz offline. Whole-body kinematics were captured simultaneously using two systems: 1) a 7-camera OMC system (Vicon MX, Vicon Motion Systems Inc., Denver, CO, US); and 2) a commercially-available IMC system (MVN, Xsens technologies B.V., Enschede, the Netherlands). Both were sampled at 60 Hz and low-pass filtered offline (10 Hz cutoff; 4th order Butterworth; bidirectional). For the OMC, passive reflective markers were placed bilaterally or in the mid-sagittal plane over several anatomical landmarks: calcaneus, first and fifth metatarsal heads, lateral and medial malleoli, lateral and medial tibial epicondyles, acromial processes, lateral and medial humeral epicondyles, radialis and ulnar styloid processes, the spinous processes of the seventh cervical (C7) and eighth thoracic (T8) vertebrae, incisura jugularis; xiphoid process, anterior and posterior iliac superior spines. In addition, clusters of 3-4 markers were placed midway between C7 and T8, and over or adjacent to IMUs at the pelvis, the lower legs, upper arms, lower arms and heels. The MVN includes 17 miniature IMUs, positioned on the head, sternum and pelvis; and bilaterally on the scapulae, the upper and lower arms, hands, thighs, shanks, and feet (Figure 2), and provides a built-in anatomical model of the human body (Roetenberg & Luinge 2009). Note that the MVN does not include an IMU over the thorax, but the system provides thoracic kinematics estimated from IMUs on the scapulae; we used thoracic kinematics from the MVN as a “virtual” IMU, and scapular IMUs were not used directly here. Data capture was done via a graphical interface (MVN Studio 3.0, Xsens technologies B.V., Enschede), and the included kinematic coupling algorithm (KiC™) was enabled to address problems with magnetic disturbances.

Figure 2. The MVN system setup, along with clusters of reflective markers.

2.3 Experimental Procedures

Initially, participants donned the MVN motion capture suit, and reflective markers and marker clusters were attached. The MVN system was then turned on (and was left on for the entire session), followed by two calibration stages (~ 30 min). The first stage involved completing four predefined calibration steps to align IMUs to the segments of a participant (see Roetenberg & Luinge 2009). These steps, as indicated in the system manual, include standing straight (N pose), standing straight with arms stretched horizontally (T pose), squatting, and moving the hands together in all directions (Hand touch). The software reports calibration quality in one of four levels (good, acceptable, fair and poor), and a minimum of Acceptable quality was ensured for each step as recommended in the system manual. The second stage was a calibration procedure (moving body segments in all directions) used to find a transformation matrix between the laboratory and MVN coordinate systems (Tsai & Lenz 1989); this was required because the OMC and the MVN system have different global coordinate systems.

Prior to the MMH trials, anatomical markers were removed after being referenced separately to clusters and IMUs on the corresponding body segments. For the latter, the markers were first transformed to the MVN coordinate system using data from the calibration trials, so that the

same anatomical landmarks were shared between the OMC and the MVN systems. In addition, and to synchronize the OMC and MVN systems, participants were instructed to perform an easily identifiable movement at the start of each trial (i.e., quickly raising a foot). All off-line data processing was completed using Matlab 7 (Mathworks™ Inc., Natick, MA, USA).

2.4 Physical exposure measures and dependent variables

Pertinent to physical exposure assessment, kinematic measures were 3-D included joint angles (i.e., between distal and proximal segments) and angular velocities of the knees, hips, trunk and shoulders. Kinetic measures included 3-D external moments at the knees, hips, L5/S1, and shoulders. Note that only sagittal plane kinematic and kinetic measures were considered for the knees.

A direct comparison of the MVN system against the OMC system in terms of quantifying physical exposures is difficult, largely due to differences in anatomical landmark locations between the systems (i.e., misalignment of the corresponding segment coordinate systems). To address such misalignment, an anatomical model was introduced, similar to the approach of Cutti *et al.* (2007), such that the IMC system shared the same anatomical landmarks as the OMC system. Specifically, all physical exposure measures were obtained using three separate *anatomical models*: 1) defined by anatomical landmarks reconstructed using the clusters (Model #0; “gold standard”); 2) defined by the IMUs of the MVN system (Model #1; intermediary model); and 3) the noted MVN built-in anatomical model (Model #2).

For each anatomical model, and based generally on International Society of Biomechanics recommendations (Wu *et al.* 2002; 2005), segmental coordinate systems were defined, and joint angles were calculated following the Z-X-Y sequence of Euler angles (respective rotations in the sagittal, frontal, and transverse planes). Joint angular velocities and moments were calculated using a homogeneous matrix approach (Doriot & Chéze 2004) that did not require an Euler sequence. Both joint angular velocities and moments were expressed in the proximal segments' coordinate systems and segmental inertial properties were estimated for each model, based on previous segment definitions (Dumas *et al.* 2007). Only the vertical force component at the ground or hand was incorporated to compute joint moments, and was applied at the ankle and elbow joint centers to enforce the same point of application of force platform measures and hand forces across the models. Note that the elbow (not the wrist) joint centers were selected here because, for some participants, clusters on the forearms were too poorly captured by the OMC system. Shoulder moments were estimated for all tasks using hand forces and a “top-down” modeling approach. L5/S1 and lower extremity joint moments were estimated “bottom-up”, for all tasks except Carrying. We did not require participants to walk on the force platforms during Carrying tasks, to elicit more naturalistic carrying behaviors. Thus, during Carrying the L5/S1 moments were estimated top-down with assumed rigid body motion of the thorax. Since participants were not required to walk on the force platforms during Carrying tasks, lower-extremity moments were not calculated or analyzed during these tasks. A representative example of the exposure measures derived using each model is presented in Figure 3.

Figure 3. Example of whole body kinematics (top) and trunk kinematics and kinetics (bottom) obtained during an asymmetric lifting trial using three Models. Model #0 is the anatomical model defined using the optical motion capture (OMC) system, Model #1 is the anatomical model defined using the inertial motion capture (IMC), and Model #2 is the MVN built-in anatomical model of the IMC system.

To assess the correspondence between measures obtained from Models #1 and #2 versus those from Model #0 (the gold standard), two comparative measures were determined:

- Mean Absolute Error (MAE): $\sum |\mathbf{B} - \mathbf{A}| / L$ where $\mathbf{A}$ and $\mathbf{B}$ are time series of exposures respectively from Model #0 and Model #1 (or #2), and L is the time series length.
- Peak Absolute Error (PAE): The larger of the differences between the positive or negative 95th percentiles of $\mathbf{B}$ and $\mathbf{A}$.

These measures were obtained separately for each trial and for all joint angle, angular velocity, and moment time series. Note that all joint angles were calculated relative to those in a neutral standing pose (N pose above) during upright stance (i.e., all joint angles were zero in this pose).

2.4 Statistical analyses

Comparative measures were obtained using three separate anatomical models (*Model*), at multiple joints (*Joint*), during five *Task*, and over three *Time Blocks*. Correspondingly, four-way, repeated-measures analysis of variance (RANOVA) was performed separately on each comparative measure. Since lower-extremity joint moments were not obtained for Carrying tasks, separate RANOVAs were performed on comparative measures of joint moments with tasks excluding Carrying and only with Carrying. In all analyses, bilateral measures were pooled, and all comparative measures were log-transformed prior to statistical analyses to achieve normally distributed residuals. Significant effects were examined using LSmean post-hoc contrasts. All statistical analyses were complete using JMP 9.0 (SAS Institute Inc., Cary, NC, USA) with statistical significance determined when $p \leq .01$. All summary data are presented as means (95% Confidence Intervals).

3. Results

3.1 Joint angles

Significant main and interactive effects of *Time Block* were observed on many MAE and PAE values of joint angles. Specifically, *Time Block* and its interactions with *Joint*, *Task*, and *Joint x Task* affected all MAE ($p \leq 0.01$) and PAE values ($p \leq 0.0051$), except that *Time Block x Joint* interactions had no significant effects on MAE_x . Post-hoc contrasts for these *Time Block*-related effects showed that such effects were varied across task and joint conditions, but typically caused larger MAE and PAE values for Time Blocks 2 and 3 vs. Time Block 1. Across

all combinations of joint and task, the magnitude of differences between time blocks was $\leq 0.8^\circ$, 3.63° , and 0.6° for MAE_x , MAE_y , and MAE_z , respectively; and $\leq 0.44^\circ$, 2.72° , and 0.85° for PAE_x , PAE_y , and PAE_z , respectively.

Joint, *Task*, and/or *Model* had significant main and interaction effects on all MAE and PAE values. In particular, *Joint* $\times$ *Task* ($p < 0.0001$) and *Joint* $\times$ *Task* $\times$ *Model* ($p \leq 0.0021$) interactions significantly influenced all the measures, except that the latter had no significant effects on PAE_y . A summary of all measures is thus presented for each joint, task and model (Table 1), which reveals that the performance of Models #1 and #2 was comparable, and that this performance appeared to be associated with the specific kinematic characteristics required for a given task (e.g., whole body, predominantly shoulder movements, etc.).

Table 1. Summary statistics [LSmean (95% CI)] of comparative measures (MAE and PAE) for joint angles. Values of 95% CI were obtained after pooling all measures in each time block. Note that Model #0 is the anatomical model defined using the optical motion capture (OMC) system; Model #1 is the anatomical model defined using the inertial motion capture (IMC) system while sharing the same anatomical landmarks with the OMC system; and Model #2 is the MVN built-in anatomical model of the IMC system.

Axis	Task	Model #1 vs. Model #0				Model #2 vs. Model #0			
		L5/S1	Shoulder	Hip	Knee	L5/S1	Shoulder	Hip	Knee
MAE (deg)	X	LL _{GROUND}	1.51 (1.32, 1.72)	3.68 (3.28, 4.11)	2.39 (2.14, 2.68)	1.89 (1.66, 2.16)	5.13 (4.58, 5.74)	3.34 (2.98, 3.74)	
		LL _{KNUCKLE}	1.42 (1.25, 1.62)	2.24 (2.00, 2.51)	1.63 (1.46, 1.83)	1.11 (0.97, 1.27)	2.82 (2.52, 3.16)	1.05 (0.93, 1.17)	
		LL _{ASYM}	2.50 (2.19, 2.86)	4.04 (3.61, 4.52)	2.64 (2.36, 2.96)	2.00 (1.75, 2.29)	4.34 (3.88, 4.86)	1.91 (1.71, 2.14)	
		Carrying	1.54 (1.34, 1.75)	1.40 (1.25, 1.57)	2.22 (1.98, 2.48)	1.48 (1.30, 1.69)	1.44 (1.29, 1.61)	2.13 (1.91, 2.39)	
		PushPull	0.89 (0.78, 1.01)	3.15 (2.81, 3.52)	0.99 (0.88, 1.10)	0.76 (0.66, 0.86)	4.19 (3.74, 4.69)	0.68 (0.60, 0.76)	
	Y	LL _{GROUND}	2.51 (2.24, 2.83)	2.52 (2.30, 2.75)	3.17 (2.90, 3.46)	2.50 (2.22, 2.81)	2.55 (2.34, 2.79)	4.83 (4.42, 5.28)	
		LL _{KNUCKLE}	2.86 (2.54, 3.21)	2.77 (2.54, 3.03)	4.73 (4.33, 5.17)	2.88 (2.56, 3.24)	2.89 (2.64, 3.16)	4.46 (4.08, 4.88)	
		LL _{ASYM}	3.09 (2.75, 3.48)	2.68 (2.45, 2.93)	3.24 (2.97, 3.55)	3.11 (2.77, 3.50)	3.02 (2.76, 3.30)	3.37 (3.08, 3.68)	
		Carrying	1.54 (1.37, 1.73)	1.13 (1.04, 1.24)	2.81 (2.57, 3.07)	1.60 (1.42, 1.80)	1.13 (1.04, 1.24)	3.56 (3.25, 3.89)	
		PushPull	2.40 (2.13, 2.70)	2.53 (2.32, 2.77)	2.26 (2.07, 2.47)	2.41 (2.14, 2.71)	2.62 (2.40, 2.86)	2.36 (2.16, 2.58)	
	Z	LL _{GROUND}	4.84 (4.28, 5.47)	5.97 (5.39, 6.62)	2.88 (2.60, 3.19)	4.56 (4.04, 5.15)	4.96 (4.48, 5.50)	2.42 (2.19, 2.69)	3.07 (2.77, 3.40)
		LL _{KNUCKLE}	1.63 (1.44, 1.84)	2.59 (2.34, 2.87)	1.69 (1.53, 1.88)	1.49 (1.32, 1.68)	2.88 (2.60, 3.19)	0.93 (0.84, 1.03)	1.55 (1.40, 1.72)
		LL _{ASYM}	2.27 (2.01, 2.57)	3.99 (3.60, 4.42)	2.32 (2.09, 2.57)	1.53 (1.35, 1.73)	3.17 (2.86, 3.51)	1.37 (1.24, 1.52)	1.78 (1.61, 1.98)
		Carrying	1.31 (1.16, 1.48)	1.36 (1.23, 1.51)	2.00 (1.81, 2.22)	3.40 (3.07, 3.77)	1.16 (1.03, 1.31)	1.41 (1.27, 1.56)	2.30 (2.07, 2.54)
		PushPull	1.66 (1.47, 1.88)	4.17 (3.76, 4.62)	1.10 (1.00, 1.22)	1.50 (1.33, 1.69)	3.69 (3.33, 4.08)	0.88 (0.79, 0.98)	1.30 (1.17, 1.44)
	X	LL _{GROUND}	0.85 (0.68, 1.06)	2.24 (1.89, 2.65)	1.67 (1.41, 1.97)	1.21 (0.96, 1.51)	3.12 (2.64, 3.70)	2.19 (1.85, 2.59)	
		LL _{KNUCKLE}	0.73 (0.59, 0.92)	1.74 (1.47, 2.07)	0.98 (0.82, 1.16)	0.59 (0.47, 0.74)	2.41 (2.03, 2.85)	0.74 (0.63, 0.88)	
		LL _{ASYM}	1.55 (1.24, 1.94)	1.83 (1.54, 2.17)	1.28 (1.08, 1.52)	1.17 (0.93, 1.46)	2.90 (2.45, 3.44)	0.96 (0.81, 1.14)	
		Carrying	0.83 (0.66, 1.04)	0.87 (0.74, 1.03)	1.36 (1.15, 1.61)	1.12 (0.89, 1.40)	0.9 (0.76, 1.07)	1.08 (0.91, 1.28)	
		PushPull	0.60 (0.48, 0.75)	1.88 (1.59, 2.22)	0.64 (0.54, 0.75)	0.41 (0.33, 0.51)	1.66 (1.40, 1.97)	0.42 (0.36, 0.50)	
	Y	LL _{GROUND}	1.46 (1.20, 1.79)	1.78 (1.54, 2.06)	2.07 (1.78, 2.40)	1.48 (1.21, 1.81)	1.88 (1.62, 2.18)	3.09 (2.67, 3.58)	
		LL _{KNUCKLE}	1.85 (1.51, 2.26)	2.19 (1.89, 2.54)	3.38 (2.92, 3.91)	1.93 (1.58, 2.36)	1.59 (1.38, 1.85)	3.27 (2.82, 3.79)	
		LL _{ASYM}	2.03 (1.66, 2.49)	1.75 (1.51, 2.03)	2.99 (2.58, 3.46)	1.93 (1.57, 2.36)	2.08 (1.79, 2.41)	3.26 (2.82, 3.78)	
		Carrying	0.96 (0.79, 1.18)	0.87 (0.75, 1.00)	2.05 (1.77, 2.38)	1.09 (0.89, 1.34)	0.76 (0.66, 0.89)	2.32 (2.00, 2.69)	
		PushPull	1.40 (1.15, 1.72)	1.91 (1.65, 2.22)	1.53 (1.32, 1.78)	1.40 (1.14, 1.72)	1.85 (1.59, 2.14)	1.55 (1.34, 1.80)	
	Z	LL _{GROUND}	7.20 (5.85, 8.85)	4.82 (4.12, 5.62)	2.22 (1.90, 2.59)	1.44 (1.23, 1.68)	7.33 (5.97, 9.02)	5.35 (4.58, 6.25)	1.64 (1.40, 1.91)
		LL _{KNUCKLE}	1.67 (1.36, 2.05)	1.68 (1.44, 1.96)	1.33 (1.14, 1.55)	1.00 (0.86, 1.17)	1.56 (1.27, 1.91)	2.00 (1.71, 2.34)	0.83 (0.71, 0.97)
		LL _{ASYM}	1.33 (1.08, 1.64)	2.80 (2.40, 3.27)	2.04 (1.75, 2.39)	1.17 (1.00, 1.36)	0.93 (0.75, 1.14)	2.62 (2.24, 3.06)	1.19 (1.02, 1.39)
		Carrying	0.93 (0.76, 1.14)	0.94 (0.80, 1.09)	1.27 (1.09, 1.49)	0.91 (0.78, 1.07)	0.81 (0.66, 0.99)	1.01 (0.87, 1.18)	1.31 (1.13, 1.53)
		PushPull	1.29 (1.05, 1.59)	4.86 (4.17, 5.68)	0.85 (0.73, 1.00)	0.64 (0.55, 0.75)	1.39 (1.13, 1.71)	5.45 (4.67, 6.36)	0.76 (0.65, 0.88)

- X, Y, and Z indicate values in the frontal, transverse and sagittal planes, respectively.
- For a given task, largest values across joints are highlighted in bold.

3.2 Joint angular velocities

All MAE values were significantly affected by *Time Block* and/or *Time Block* $\times$ *Task* interactions ($p \leq 0.0057$), such that values were larger for Time Block 3 vs. Time Blocks 1 and 2. For a given task, the magnitude of differences between time blocks was $\leq 0.61^\circ/\text{s}$, $0.53^\circ/\text{s}$, and $1.03^\circ/\text{s}$ for MAE_x , MAE_y , and MAE_z , respectively. *Time Block* had no significant effects on PAE values ($p \geq 0.047$), and no obvious trends associated with *Time Block* were observed for any given joint and/or task.

All MAE and PAE values were influenced by *Joint*, *Task*, and/or *Model*. Significant interactions of *Joint* $\times$ *Task* ($p < 0.0001$) and *Joint* $\times$ *Task* $\times$ *Model* ($p \leq 0.0024$) especially affected all the measures, except that the latter had no effects on PAE_y . For each joint, task, and model, all measures are summarized in Table 2, which permitted similar observations on performance as noted above for joint angles.

Table 2. Summary statistics [LSmean (95% CI)] of comparative measures (MAE and PAE) for joint angular velocities. See text or Table 1 caption for model descriptions.

	Axis	Task	Model #1 vs. Model #0				Model #2 vs. Model #0			
			L5/S1	Shoulder	Hip	Knee	L5/S1	Shoulder	Hip	Knee
MAE (deg/s)	X	LL _{GROUND}	3.27 (2.95, 3.62)	5.88 (5.38, 6.42)	5.33 (4.88, 5.83)		3.70 (3.34, 4.10)	7.09 (6.49, 7.75)	8.15 (7.46, 8.91)	
		LL _{KNUCKLE}	1.38 (1.25, 1.53)	2.90 (2.66, 3.17)	1.09 (0.99, 1.19)		1.36 (1.23, 1.51)	2.98 (2.73, 3.26)	0.97 (0.89, 1.06)	
		LL _{ASYM}	4.27 (3.85, 4.73)	5.27 (4.83, 5.76)	3.58 (3.28, 3.91)		3.94 (3.56, 4.37)	5.05 (4.62, 5.52)	3.80 (3.47, 4.15)	
		Carrying	5.33 (4.81, 5.91)	4.52 (4.14, 4.94)	8.42 (7.71, 9.21)		6.08 (5.48, 6.74)	4.11 (3.76, 4.49)	7.67 (7.02, 8.38)	
		PushPull	1.99 (1.79, 2.20)	6.43 (5.88, 7.02)	1.68 (1.54, 1.84)		1.90 (1.71, 2.10)	8.51 (7.79, 9.30)	1.26 (1.15, 1.38)	
	Y	LL _{GROUND}	3.91 (3.59, 4.26)	5.77 (5.36, 6.21)	3.95 (3.67, 4.25)		4.06 (3.73, 4.43)	4.69 (4.36, 5.04)	5.86 (5.45, 6.31)	
		LL _{KNUCKLE}	1.93 (1.77, 2.10)	3.06 (2.84, 3.29)	1.10 (1.02, 1.18)		1.90 (1.75, 2.07)	2.91 (2.70, 3.13)	1.21 (1.12, 1.30)	
		LL _{ASYM}	4.45 (4.08, 4.84)	4.90 (4.55, 5.27)	3.11 (2.89, 3.34)		4.73 (4.35, 5.16)	4.45 (4.13, 4.78)	3.40 (3.16, 3.66)	
		Carrying	3.59 (3.29, 3.91)	1.87 (1.74, 2.02)	6.41 (5.96, 6.90)		3.94 (3.61, 4.29)	1.80 (1.67, 1.94)	11.70 (10.94, 12.67)	
		PushPull	3.48 (3.20, 3.79)	6.20 (5.76, 6.68)	1.34 (1.24, 1.44)		3.48 (3.19, 3.79)	5.52 (5.13, 5.96)	1.47 (1.37, 1.59)	
	Z	LL _{GROUND}	9.54 (8.59, 10.60)	10.87 (9.87, 11.97)	6.21 (5.64, 6.83)	5.70 (5.17, 6.27)	9.46 (8.51, 10.51)	9.51 (8.64, 10.48)	5.69 (5.16, 6.26)	5.87 (5.33, 6.47)
		LL _{KNUCKLE}	2.38 (2.14, 2.64)	3.44 (3.13, 3.79)	1.32 (1.19, 1.45)	0.91 (0.83, 1.00)	2.33 (2.10, 2.59)	3.44 (3.13, 3.79)	1.24 (1.13, 1.37)	0.86 (0.78, 0.95)
		LL _{ASYM}	4.25 (3.82, 4.72)	6.14 (5.58, 6.76)	3.82 (3.47, 4.21)	3.27 (2.97, 3.60)	3.47 (3.13, 3.86)	4.78 (4.34, 5.26)	3.05 (2.77, 3.36)	2.31 (2.10, 2.54)
		Carrying	3.59 (3.23, 3.99)	3.23 (2.93, 3.55)	7.86 (7.14, 8.65)	10.60 (9.62, 11.67)	2.62 (2.36, 2.91)	2.67 (2.42, 2.94)	10.72 (9.73, 11.80)	11.63 (10.56, 12.81)
		PushPull	3.97 (3.57, 4.41)	7.76 (7.05, 8.54)	1.80 (1.63, 1.98)	1.30 (1.18, 1.43)	3.69 (3.32, 4.10)	7.83 (7.11, 8.62)	1.57 (1.43, 1.73)	1.08 (0.98, 1.18)
	X	LL _{GROUND}	2.30 (1.85, 2.86)	6.13 (5.18, 7.26)	4.04 (3.41, 4.78)		2.46 (1.98, 3.07)	8.65 (7.31, 10.25)	6.06 (5.12, 7.18)	
		LL _{KNUCKLE}	1.18 (0.95, 1.48)	3.57 (3.01, 4.23)	0.77 (0.65, 0.92)		0.84 (0.68, 1.05)	2.90 (2.45, 3.43)	0.68 (0.57, 0.80)	
		LL _{ASYM}	3.19 (2.56, 3.97)	4.31 (3.64, 5.10)	2.39 (2.02, 2.83)		3.22 (2.59, 4.02)	4.10 (3.46, 4.85)	3.13 (2.65, 3.71)	
		Carrying	2.84 (2.28, 3.54)	2.44 (2.06, 2.89)	4.75 (4.01, 5.63)		3.46 (2.78, 4.31)	2.31 (1.95, 2.74)	5.13 (4.33, 6.08)	
		PushPull	1.24 (0.99, 1.54)	6.03 (5.09, 7.14)	1.10 (0.93, 1.30)		1.26 (1.01, 1.58)	10.03 (8.47, 11.87)	0.93 (0.79, 1.10)	
	Y	LL _{GROUND}	2.93 (2.36, 3.63)	5.54 (4.71, 6.51)	3.33 (2.83, 3.91)		3.24 (2.61, 4.02)	4.49 (3.82, 5.28)	5.40 (4.59, 6.35)	
		LL _{KNUCKLE}	1.80 (1.46, 2.24)	2.47 (2.10, 2.91)	0.72 (0.61, 0.85)		1.69 (1.36, 2.10)	2.45 (2.09, 2.89)	0.86 (0.73, 1.01)	
		LL _{ASYM}	3.80 (3.06, 4.71)	3.76 (3.20, 4.42)	2.31 (1.97, 2.71)		4.59 (3.70, 5.69)	3.71 (3.16, 4.36)	2.64 (2.25, 3.10)	
		Carrying	3.57 (2.88, 4.43)	1.32 (1.13, 1.56)	3.48 (2.96, 4.09)		2.71 (2.18, 3.36)	1.36 (1.16, 1.60)	4.02 (3.42, 4.72)	
		PushPull	2.29 (1.85, 2.84)	5.51 (4.69, 6.48)	0.97 (0.82, 1.13)		2.26 (1.83, 2.81)	5.06 (4.31, 5.95)	1.18 (1.00, 1.38)	
	Z	LL _{GROUND}	19.17 (15.52, 23.66)	12.73 (10.82, 14.99)	5.27 (4.48, 6.20)	5.48 (4.65, 6.45)	19.16 (15.52, 23.66)	15.30 (13.00, 18.01)	5.81 (4.93, 6.83)	6.46 (5.49, 7.61)
		LL _{KNUCKLE}	2.55 (2.07, 3.15)	3.11 (2.64, 3.66)	1.40 (1.19, 1.65)	0.77 (0.65, 0.91)	2.60 (2.11, 3.21)	4.10 (3.48, 4.82)	1.18 (1.00, 1.39)	0.75 (0.64, 0.89)
		LL _{ASYM}	3.19 (2.58, 3.93)	4.80 (4.08, 5.65)	2.70 (2.29, 3.18)	2.51 (2.14, 2.96)	3.25 (2.63, 4.01)	4.86 (4.13, 5.72)	1.84 (1.56, 2.17)	2.05 (1.74, 2.41)
		Carrying	2.34 (1.90, 2.89)	3.19 (2.71, 3.76)	3.57 (3.04, 4.21)	6.03 (5.13, 7.10)	1.36 (1.10, 1.68)	2.68 (2.28, 3.16)	2.67 (2.26, 3.14)	7.21 (6.12, 8.48)
		PushPull	5.53 (4.48, 6.83)	5.91 (5.02, 6.96)	2.18 (1.86, 2.57)	1.03 (0.88, 1.22)	4.10 (3.32, 5.06)	6.26 (5.32, 7.36)	1.31 (1.11, 1.54)	0.83 (0.70, 0.98)

3.3 Joint moments

Relatively few *Time Block*-related effects were observed on the comparative measures for joint moments, except that *Time Block* interacted significantly with *Model* on MAE_x ($p < 0.0001$), and had a significant main effect on MAE_z ($p = 0.0025$). Also, *Time Block* $\times$ *Model* interactions were marginally significant on PAE_x ($p = 0.021$). A difference in MAE_x and PAE_x values between time blocks of ≤ 0.30 Nm and 0.27 Nm were found, respectively, for Model #1; and ≤ 0.32 Nm and 0.44 Nm for Model #2.

The main and all interactive effects of *Joint*, *Task*, and *Model* significantly affected all MAE and PAE values ($p < 0.0001$), except that there were no significant three-way interaction effects on PAE_z ($p = 0.048$). In the case of Carrying, *Joint* and *Model* had significant main effects on all MAE values ($p \leq 0.002$), and interaction effects were found on MAE_y ($p = 0.0021$). *Joint* significantly affected all PAE values ($p < 0.0001$), and *Model* effects on PAE_y approached significance ($p = 0.012$) and significantly affected PAE_z ($p < 0.0001$). Accordingly, all the comparative measures were summarized in Table 3 for each joint, task, and model. Therein, it was observed that, similar to joint angles and angular velocities, the performance differed in relation to characteristics of the different tasks. Of note, Model #1 generally outperformed Model #2 for joint moments, in contrast to kinematics as summarized above.

Table 3. Summary statistics [LSmean (95% CI)] of comparative measures (MAE and PAE) for joint moments. See text or Table 1 caption for model descriptions.

	Axis	Task	Model #1 vs. Model #0				Model #2 vs. Model #0			
			L5/S1	Shoulder	Hip	Knee	L5/S1	Shoulder	Hip	Knee
MAE (Nm)	X	LL _{GROUND}	6.74 (5.77, 7.87)	1.11 (0.96, 1.27)	4.86 (4.23, 5.58)		13.89 (11.89, 16.22)	1.28 (1.12, 1.47)	10.64 (9.26, 12.22)	
		LL _{KNUCKLE}	4.92 (4.21, 5.75)	0.50 (0.44, 0.57)	2.64 (2.30, 3.04)		7.66 (6.56, 8.95)	1.30 (1.13, 1.49)	12.34 (10.74, 14.17)	
		LL _{ASYM}	12.67 (10.85, 14.80)	0.72 (0.63, 0.83)	6.73 (5.86, 7.73)		34.22 (29.3, 39.96)	1.43 (1.25, 1.64)	14.4 (12.54, 16.54)	
		Carrying	5.21 (4.43, 6.11)	0.77 (0.67, 0.89)			5.75 (4.90, 6.75)	0.99 (0.86, 1.14)		
		PushPull	4.44 (3.80, 5.18)	0.11 (0.10, 0.13)	2.47 (2.15, 2.84)		8.05 (6.90, 9.41)	1.50 (1.30, 1.72)	10.70 (9.32, 12.29)	
	Y	LL _{GROUND}	3.77 (3.12, 4.55)	0.68 (0.57, 0.81)	2.43 (2.04, 2.89)		6.90 (5.72, 8.33)	1.00 (0.84, 1.19)	6.14 (5.16, 7.31)	
		LL _{KNUCKLE}	1.00 (0.83, 1.20)	0.25 (0.21, 0.30)	0.62 (0.52, 0.74)		2.14 (1.77, 2.58)	0.48 (0.40, 0.57)	2.92 (2.46, 3.48)	
		LL _{ASYM}	3.87 (3.21, 4.67)	0.37 (0.31, 0.44)	2.01 (1.69, 2.39)		10.26 (8.51, 12.39)	0.64 (0.54, 0.76)	4.30 (3.61, 5.12)	
		Carrying	0.99 (0.74, 1.32)	0.37 (0.28, 0.49)			1.18 (0.89, 1.57)	0.57 (0.43, 0.75)		
		PushPull	1.07 (0.89, 1.29)	0.05 (0.04, 0.06)	0.71 (0.60, 0.84)		2.61 (2.16, 3.15)	0.24 (0.20, 0.28)	3.17 (2.66, 3.77)	
	Z	LL _{GROUND}	14.34 (11.75, 17.52)	1.43 (1.19, 1.71)	7.55 (6.29, 9.06)	2.38 (1.98, 2.85)	16.50 (13.52, 20.15)	2.20 (1.83, 2.64)	8.23 (6.86, 9.88)	6.59 (5.50, 7.91)
		LL _{KNUCKLE}	7.95 (6.51, 9.71)	0.75 (0.63, 0.91)	4.20 (3.50, 5.04)	1.55 (1.29, 1.85)	11.40 (9.33, 13.92)	1.38 (1.15, 1.65)	6.19 (5.16, 7.43)	5.60 (4.67, 6.71)
		LL _{ASYM}	13.61 (11.14, 16.62)	0.84 (0.70, 1.01)	7.19 (5.99, 8.62)	2.54 (2.11, 3.04)	20.02 (16.39, 24.45)	1.27 (1.06, 1.53)	9.91 (8.26, 11.89)	6.50 (5.42, 7.79)
		Carrying	4.39 (3.67, 5.23)	0.99 (0.85, 1.16)			8.23 (6.90, 9.83)	1.94 (1.66, 2.26)		
		PushPull	5.55 (4.55, 6.78)	0.16 (0.13, 0.19)	3.70 (3.08, 4.43)	1.34 (1.12, 1.61)	9.82 (8.04, 12.00)	0.55 (0.45, 0.65)	5.77 (4.81, 6.92)	4.67 (3.89, 5.60)
PAE (Nm)	X	LL _{GROUND}	4.06 (3.17, 5.20)	0.48 (0.39, 0.58)	3.16 (2.58, 3.87)		9.08 (7.09, 11.62)	0.88 (0.72, 1.07)	5.56 (4.54, 6.82)	
		LL _{KNUCKLE}	3.06 (2.39, 3.92)	0.17 (0.14, 0.20)	1.92 (1.56, 2.35)		4.30 (3.36, 5.50)	1.17 (0.96, 1.44)	7.54 (6.16, 9.24)	
		LL _{ASYM}	7.77 (6.06, 9.94)	0.24 (0.20, 0.30)	3.32 (2.71, 4.07)		26.25 (20.50, 33.61)	1.23 (1.01, 1.51)	8.57 (6.99, 10.50)	
		Carrying	2.12 (1.69, 2.66)	0.68 (0.57, 0.82)			2.33 (1.86, 2.93)	0.87 (0.72, 1.04)		
		PushPull	2.86 (2.24, 3.67)	0.12 (0.10, 0.15)	1.65 (1.34, 2.02)		3.47 (2.71, 4.44)	1.15 (0.94, 1.41)	6.79 (5.54, 8.32)	
	Y	LL _{GROUND}	3.32 (2.54, 4.35)	0.38 (0.30, 0.47)	1.68 (1.35, 2.09)		6.06 (4.63, 7.92)	0.57 (0.46, 0.71)	3.54 (2.85, 4.41)	
		LL _{KNUCKLE}	0.69 (0.53, 0.90)	0.16 (0.13, 0.20)	0.37 (0.30, 0.46)		1.37 (1.05, 1.79)	0.29 (0.24, 0.37)	1.78 (1.43, 2.21)	
		LL _{ASYM}	2.77 (2.12, 3.62)	0.16 (0.13, 0.20)	1.33 (1.07, 1.66)		7.87 (6.01, 10.30)	0.27 (0.22, 0.34)	3.68 (2.96, 4.58)	
		Carrying	0.62 (0.44, 0.88)	0.27 (0.20, 0.38)			0.78 (0.55, 1.10)	0.34 (0.24, 0.47)		
		PushPull	0.61 (0.46, 0.80)	0.05 (0.04, 0.06)	0.53 (0.43, 0.67)		1.33 (1.01, 1.73)	0.23 (0.19, 0.29)	2.00 (1.61, 2.49)	
	Z	LL _{GROUND}	14.42 (10.69, 19.44)	1.85 (1.43, 2.40)	9.27 (7.17, 11.99)	1.35 (1.05, 1.75)	15.21 (11.28, 20.51)	2.76 (2.14, 3.58)	8.19 (6.33, 10.59)	3.29 (2.54, 4.25)
		LL _{KNUCKLE}	5.43 (4.03, 7.33)	0.28 (0.22, 0.36)	3.09 (2.39, 4.00)	1.25 (0.96, 1.61)	6.12 (4.54, 8.26)	0.60 (0.46, 0.77)	3.85 (2.98, 4.98)	4.07 (3.14, 5.26)
		LL _{ASYM}	10.31 (7.65, 13.90)	0.53 (0.41, 0.69)	11.18 (8.64, 14.45)	0.65 (0.50, 0.83)	15.64 (11.60, 21.09)	0.89 (0.69, 1.15)	13.38 (10.35, 17.31)	1.37 (1.06, 1.77)
		Carrying	2.18 (1.71, 2.77)	0.77 (0.63, 0.94)			4.19 (3.29, 5.33)	1.67 (1.37, 2.03)		
		PushPull	4.12 (3.06, 5.56)	0.12 (0.09, 0.15)	2.63 (2.04, 3.41)	0.92 (0.71, 1.20)	7.18 (5.32, 9.68)	0.39 (0.30, 0.50)	3.73 (2.89, 4.83)	2.82 (2.18, 3.65)

4. Discussion

The study examined the performance of a commercially-available IMC system to quantify physical exposures over time – specifically, angles, angular velocities, and moments at selected body parts. For many comparative measures of physical exposures there was a statistically significant change in performance over time. Yet, these change seemed to be relatively minor and suggest limited practical relevance (e.g., the magnitude of MAE differences between time blocks for joint angles was $\leq 3.63^\circ$). This suggests that the performance of the MVN system is rather stable over the time period examined. Moreover, and consistent with existing studies, the accuracy of kinematics captured by the IMC system varied more substantially across different MMH tasks, and generally consistent with the movement characteristics involved for tasks (cf. Tables 1 and 2).

For joint angles, mean MAE and PAE values, in several cases, exceeded the root-mean-square accuracy of an individual IMU in orientation, as noted by the manufacturer ($\leq 3^\circ$ in a dynamic condition), and in particular the upper bounds of 95% CIs for MAE and PAE values were about two and three times (5.74° and 9.02° , respectively) the noted accuracy. Those errors were apparent both with the intermediary model (Model #1, IMC with reflective markers) and the MVN built-in anatomical model (Model #2), which suggests that the observed errors are not simply due to misalignments between segment coordinate systems defined separately using the OMC and the IMC system. Although not directly comparable, existing studies have reported similar findings, in that a typical orientation error was 8.3° in an upright posture, $3^\circ - 21.7^\circ$ during level walking (Picerno *et al.*, 2008), $\sim 5^\circ - \sim 20^\circ$ for arm motions during daily tasks (Luinge *et al.*, 2007), and $0.6^\circ - 25.6^\circ$ during dynamic whole-body tasks (Godwin, *et al.*, 2009). Yet, for controlled single-joint-movements of the shoulder or the elbow, smaller errors ($< 3.6^\circ$) were found (Cutti *et al.*, 2007). In general, these noted studies with dynamic task conditions found larger mean errors versus the current results, which may be explained by the MVN built-in anatomical model of the IMC system. The built-in model estimates segment orientations by facilitating joint kinematic constraints and aiding IMUs (Roetenberg & Luinge 2009), so that the built-in model likely yields a smaller estimation error in segmental orientation than an individual IMU.

In addition, the magnitude of MAE and PAE values for joint angles and angular velocities varied with joint axes of rotation, joints, and tasks (Tables 1 and 2), which agrees collectively with the findings from existing studies (Brodie *et al.* 2008; Godwin *et al.* 2009; Picerno *et al.* 2008). Authors of these studies argued that the vendor's algorithm for orientation estimation is not optimal in all situations; and, in particular, Godwin *et al.* (2009) noted that estimation errors were larger in non-dominant axes of motion than in a predominant axis. Thus, caution may need to be exercised in using the system for exposure assessment in practice. For example, if the nature of different tasks involves differing predominant joint movements (e.g., shoulders in a push/pull task versus hips and knees for a carrying task), kinematics captured by the IMC system may have substantially different error magnitudes. Relative to peak joint kinematics obtained using the OMC system, the MVN built-in model yielded values different by up to ~ 20 , 14 , and 13% , respectively, in the frontal, the transverse, and the sagittal planes for joint angles; and ~ 27 , 24 , and 28% for joint angular velocities. In addition, a qualitative assessment

indicated that peak joint kinematics from the MVN built-in model tend to be underestimated compared to those from the OMC system in the sagittal plane and overestimated in other planes.

While the intermediary model and the MVN built-in model performed similarly in capturing joint kinematics, the latter exhibited poorer performance in joint moment estimations (Table 3). A follow-up observation on trial recordings with the MVN Studio 3.0 indicated that the MVN model, to some degree, incorrectly reflected the actual extremity positions of the participant. Relative to peak joint moments from Model #0, the MVN built-in anatomical model resulted in errors up to ~ 57, 63, and 39%, respectively, in the frontal, the transverse and the sagittal planes, whereas corresponding errors with the intermediary model were 24, 38, and 14%. One could view the intermediary model as the MVN built-in anatomical model if the MVN calibration could ensure the MVN built-in model to reflect relative positions of each body segments of a wearer in an absolute sense. That is, if the MVN built-in model can reflect relative positions of body segments of a wearer more correctly, the performance of the MVN built-in model ideally can be the same as the intermediary model. The performance of the former can be expected to improve further with improved estimates of joint kinematics. For example, Faber et al. (2010) estimated joint moment during lifting using orientation sensors (defined with clusters of optoelectronic markers), and reported errors in moment estimations of less than ~15%. These orientation sensors were defined using an OMC system, and thus their measurement performance was likely unaffected by the direction and speed of motions as occurs with an IMU.

Several limitations in the present work should be acknowledged. First, the performance of the MVN system may be affected by ferromagnetic disturbances that can distort orientations registered by an IMU. However, we visually checked, using the MVN Studio 3.0, that there were no strong ferromagnetic disturbances in the vicinity of the area for the experiment (equipped with force platforms and the tables). Thus, no substantial performance degradation was expected with the MVN system, though some such degradation may have existed. Second, the sampling frequency (60 Hz) that we used for the OMC and IMC systems can lead to signal misalignments up to half the sampling interval (~ 8 ms), and such misalignments may yield errors in MAE values. However, we visually evaluated the quality of signal synchronization for all trials, and no peculiar degradation in such quality was observed. Third, only vertical forces were considered in the calculation of joint moments. Since the OMC and the MVN systems have distinct global coordinate systems, it is challenging to ensure the same alignment of shear forces relative to the anatomical models, and thus shear forces were excluded to control for a potential error source. Though the magnitude of shear vs. vertical forces is generally small except for the push/pull task, the exclusion of shear forces in joint moment estimation likely affected the magnitude of errors, and which could have systematically affected errors in the push/pull task.

This study examined the performance of the IMC system in quantifying physical exposures for several MMH tasks over a relatively prolonged period of time. Overall, our results showed that the system is reasonably stable in estimating physical exposures over time, and appears to perform better than using individual IMUs. However, and as has been found in existing studies

using individual IMUs, the performance of the IMC system depended on kinematic characteristics of a task (e.g., dominant joint, speed of motion, etc.). Specifically, if a task involved relatively large movements about a given axis and joint, kinematic and kinetic errors for this axis/joint were typically relatively large. Caution should thus be taken with: 1) direct numerical comparisons of physical exposure measures obtained using the OMC vs. the IMC system, 2) direct numerical comparisons of such measures obtained using the IMC system between different tasks (e.g., larger errors observed typically with whole body dynamic tasks such as lifting from the ground and asymmetrical lifting); and 3) extracting time-dependent measures (e.g., cumulative measure) of physical exposures, since mean absolute errors were often larger than peak absolute errors. Despite these potential limitations, the IMC system demonstrated a reasonable capacity for capturing physical exposure data in the field for an extended period; the primary utility may be in assessing physical exposure differences between tasks or work conditions. Such an application would help accumulate realistic exposure data with incorporation of wearable/portable kinetic measurement systems [e.g., instrumented handles (Marras *et al.*, 2010) and/or shoes (Faber *et al.*, 2012), pressure insoles (Forner-Cordero *et al.*, 2006)], and can thereby facilitate better understandings of dose-exposure relationships and designing laboratory studies with higher ecological validity. To further advance the use of an IMC system in physical exposure assessments, future studies need to focus on improving the performance of an IMU system under dynamic conditions, and documenting performance limits of an IMC system in quantifying physical exposures under actual work environments (e.g., detectable difference in physical exposures in various occupational settings).

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4.2. Aligning data from two wearable sensor technologies for field assessments

Kim S, Nussbaum MA: [2014] Evaluation of two approaches for aligning data obtained from a motion capture system and an in-shoe pressure measurement system. *Sensors* 14:16994-17007.

Abstract: An in-shoe pressure measurement (IPM) system can be used to measure center of pressure (COP) locations, and has fewer restrictions compared to the more conventional approach using a force platform. The insole of an IPM system, however, has its own coordinate system. To use an IPM system along with a motion capture system, there is thus a need to align the coordinate systems of the two measurement systems. To address this need, the current study examined two different approaches—rigid body transformation and nonlinear mapping (*i.e.*, multilayer feed-forward neural network (MFNN))—to express COP measurements from an IPM system in the coordinate system of a motion capture system. Ten participants (five male and five female) completed several simulated manual material handling (MMH) activities, and during these activities the performance of the two approaches was assessed. Results indicated that: (1) performance varied between MMH activity types; and (2) a MFNN performed better than or comparable to the rigid body transformation, depending on the specific input variable sets used. Further, based on the results obtained, it was argued that a nonlinear mapping vs. rigid body transformation approach may be more effective to account for shoe deformation during MMH or potentially other types of physical activity.

1. Introduction

Tracking center of pressure (COP) locations under the shoe or the foot has broad utility/application in the fields of biomechanics and motor control. COP is the point of application of ground reaction forces (GRFs) that reflect the net force exerted by or on the whole body [1]. In combination with body segmental kinematics and GRFs, COP locations are required to compute joint kinetics using the bottom-up inverse dynamics approach [1,2]. Furthermore, several COP-based measures have been examined in numerous studies [3,4], to assess and understand postural control during, for example, quiet stance and gait, and to assess influences or differences related to age, gender, environmental conditions, health status, *etc.*

A force platform—a conventional system used for COP measurement—is typically fixed in the floor or other structure (e.g., stairs, walkways). Hence, and as highlighted earlier [5,6], the size, placement, and/or number of force platforms can restrict an individual's foot placement and/or the monitoring of multiple footsteps. More generally, a force platform can be difficult to use outside of a laboratory setting. To overcome such limitations, several wearable measurement systems have been introduced, such as instrumented shoe (IS) systems [7–9] and in-shoe pressure measurement (IPM) systems [5,10–12]. IS systems are typically based on two tri-axial load transducers attached externally to the shoe. This allows for measuring loads between the shoe (with the transducer) and the ground, and which can potentially provide data directly comparable to COP measurements obtained from a force platform. Externally attached transducers, however, increase both shoe height and sole rigidity [6,8]. To the authors'

knowledge, no study has formally examined how an IS system interacts with different surfaces and terrains (e.g., the effects of increased shoe height and sole rigidity on slip/trip risks). An IPM system uses a pressure-sensitive matrix (*i.e.*, insole) that can be fitted into an individual's shoe. The insole captures the plantar pressure distribution below the foot sole, and which can be easily processed to obtain the COP between the foot and the insole. Earlier studies have demonstrated that one commercial IPM system, the Pedar[®]-X, has good measurement accuracy, precision, and repeatability [13,14]. Using an IPM system, vs. an IS system, therefore appears to be more practical and valid for use in diverse environments, particularly since the former can be used with an individual's own shoe(s).

The insole of an IPM system has its own coordinate system. As such, using an IPM system along with a motion capture system (such as for assessing segmental loads through inverse dynamics) requires aligning the coordinate systems of both measurement systems. To define a transformation matrix between the two coordinate systems, existing studies have generally assumed a rigid body transformation, and used either direct or indirect methods. The direct method defines a coordinate system for the IPM system by locating insole sensors using a pointer with reflective markers [15], and thus does not require a force platform. The indirect method defines a transformation matrix by fitting COP locations between a force platform and the IPM system, either manually [10] or optimally [16–18].

In the studies noted, normal gait was a common dynamic activity of interest. Interestingly, Chumanov *et al.* [17] reported relatively larger root mean square errors (RMSE) during the starting (0%–10%) and ending stance phases (80%–100%) of gait (RMSE = ~34–57 mm and ~7–15 mm in the antero-posterior (AP) and medio-lateral (ML) directions, respectively), compared to the mid-stance phase (10%–80%) (RMSE = ~8–10 mm and ~4–7 mm in the AP and ML directions, respectively). This suggests that the rigid body transformation assumption may be less valid, since a shoe can be bent and/or otherwise deformed to varying degrees during different activities.

In the current work, we examined the performance of an optimally-defined rigid body transformation matrix between the coordinate systems of an IPM and motion capture systems. The activities of interest were those involved in manual material handling (MMH), assuming potential use of an IPM system in the context of occupational ergonomics and safety. Furthermore, and without the assumption of rigid body transformation, four different nonlinear functions were investigated that can map IPM data to COP obtained from a force platform. Specifically, we used a multilayer, feed-forward neural network (MFNN) as a mapping function with each of four different sets of input variables (extracted from IPM system outputs). The performance of the mapping functions was compared to an optimally-defined rigid body transformation.

2. Methods

2.1. Participants and Experimental Procedures

Ten young participants (19–29 years old, 5 males and 5 females) completed the study. Their mean (SD: range), stature, body mass, and foot length were 171.5 (6.9: 164–183) cm, 76.1 (13.2: 62.5–104.6) kg, and 26.8 (1.4: 24.5–28) cm, respectively. All participants reported being healthy, physically active, and having no current musculoskeletal injuries that limit their normal daily activities. Prior to any data collection, participants completed an informed consent procedure approved by the Virginia Tech Institutional Review Board.

Participants completed each of four simulated MMH activities that were intended to represent a range of occupational demands. A complete description of these activities was presented earlier [19], and as such are only summarized here. All activities were performed with a box (width $\times$ length $\times$ depth = 33 $\times$ 48.3 $\times$ 24 cm) with mass set to 20/15% of individual body mass for male/female participants. The specific MMH activities were: (a) symmetric lifting and lowering from ground to individual elbow height, and *vice versa* (LL_{GROUND}); (b) symmetric lifting and lowering from a table adjusted to individual knuckle height to individual elbow height and *vice versa* ($LL_{KNUCKLE}$); (c) asymmetric lifting and lowering from/to tables located at the side of a participant and adjusted to individual knuckle height (LL_{ASYM}); and (d) pushing and pulling away from/toward the body (PushPull). The presentation order of activities was randomized, and two trials of each activity were completed. Prior to data collection, participants were allowed to practice each MMH type until they felt comfortable and competent with each. During each trial, participants were asked to keep each foot on a separate force platform, but were allowed to move each foot freely over the force platform surface. Further, participants performed all activities using self-selected comfortable styles and speeds, and were allowed to change their working styles and speeds in each trial as desired.

2.2. Instrumentation

External foot kinetics were measured using two force platforms (AMTI OR6-7-1000, Watertown, MA, USA) and a commercial IPM system (Pedar[®]-X, Novel GmbH, Munich, Germany) with three different insole sizes covering shoe sizes of 24.8–28.3 cm. Each insole contained 99 pressure-sensitive capacitive sensors. Of note, prior to data collection, each insole was calibrated using a trublu[®] calibration device (Novel GmbH, Munich, Germany) as recommended by the manufacturer. The force platforms and the IPM system were sampled at 960 Hz and 60 Hz, respectively. Force platform outputs were low-pass filtered (15 Hz cut-off; 2nd order zero-lag Butterworth) and down-sampled to 60 Hz. Foot kinematics were captured at 60 Hz, using a 7-camera optical motion capture system (Vicon MX, Vicon Motion Systems Inc., Denver, CO, USA). Passive reflective markers were placed bilaterally on the calcaneus and 1st and 5th metatarsal heads, and a cluster of three markers was placed over the side of each shoe. Prior to the MMH activities, the 1st and 5th metatarsal head markers were removed after being referenced to the corresponding cluster, and removed markers were reconstructed using the clusters [20]. During data collection, the IPM system was synchronized with other systems via a TTL pulse (Pedar[®] Sync Box). All off-line data processing was completed using MATLAB 7 (Mathwork[™] Inc., Natick, MA, USA). When the vertical GRF from the force platform was <20 N, the foot was considered off the ground and associated COP data were excluded from subsequent analyses described below.

2.3. Transformation Matrix, T_{insole}^{Shoe} between the Insole and the Shoe Coordinate System

COP locations from the IPM system (*i.e.*, expressed in the insole coordinate system) can be transformed to the global (*i.e.*, motion capture) coordinate system [15] using:

$$\mathbf{COP}_i^{\text{Global}} = \mathbf{T}_{\text{Shoe},i}^{\text{Global}} \mathbf{T}_{\text{Insole}}^{\text{Shoe}} \mathbf{COP}_i^{\text{Insole}} \quad (1)$$

where $\mathbf{COP}_i$ is a 3×1 position vector at the i^{th} time frame. $\mathbf{T}_{\text{Shoe},i}^{\text{Global}}$ and $\mathbf{T}_{\text{Insole}}^{\text{Shoe}}$ are 4×4 transformation matrices, respectively from the shoe to the global coordinate system and from the insole to the shoe coordinate system. Using reflective markers placed on the shoe, $\mathbf{T}_{\text{Shoe},i}^{\text{Global}}$ can be defined as:

$$\mathbf{T}_{\text{Shoe},i}^{\text{Global}} = \begin{bmatrix} \mathbf{X}_i & \mathbf{Y}_i & \mathbf{Z}_i & \mathbf{O}_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

with

$$\begin{aligned} \mathbf{Y}_i &= \frac{0.5(\mathbf{MT1}_i + \mathbf{MT5}_i) - \mathbf{HEEL}_i}{\|0.5(\mathbf{MT1}_i + \mathbf{MT5}_i) - \mathbf{HEEL}_i\|} \\ \mathbf{Z}_i &= \frac{(\mathbf{MT5}_i - \mathbf{HEEL}_i) \times (\mathbf{MT1}_i - \mathbf{HEEL}_i)}{\|(\mathbf{MT5}_i - \mathbf{HEEL}_i) \times (\mathbf{MT1}_i - \mathbf{HEEL}_i)\|} \\ \mathbf{X}_i &= \mathbf{Y}_i \times \mathbf{Z}_i \end{aligned}$$

where $\mathbf{O}_i$ is a 3×1 origin vector for the shoe coordinate system and set equal to $\mathbf{HEEL}_i$ (Z coordinate is zero since COP is planar data). $\mathbf{MT1}_i$, $\mathbf{MT5}_i$ and $\mathbf{HEEL}_i$ are 3×1 position vectors of the 1st and 5th metatarsals, and the heel, respectively.

Pre-multiplying $(\mathbf{T}_{\text{Shoe},i}^{\text{Global}})^{-1}$ in Equation (1) enables defining a transformation matrix, $\mathbf{T}_{\text{Insole}}^{\text{Shoe}}$ between $(\mathbf{T}_{\text{Shoe},i}^{\text{Global}})^{-1} \mathbf{COP}_i^{\text{Global}}$ and $\mathbf{COP}_i^{\text{Insole}}$ (Figure 1), and $\mathbf{T}_{\text{Insole}}^{\text{Shoe}}$ can be solved in two different ways. In the first approach, and similar to existing studies [16–18], $\mathbf{T}_{\text{Insole}}^{\text{Shoe}}$ can be assumed as a rigid-body homogeneous transformation matrix:

$$\mathbf{T}_{\text{Insole}}^{\text{Shoe}} = \begin{bmatrix} \mathbf{R}_{\text{Insole}}^{\text{Shoe}} & \mathbf{d}_o \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

where $\mathbf{R}_{\text{Insole}}^{\text{Shoe}}$ is a 3×3 rotation matrix and $\mathbf{d}_o$ is a 3×1 translation vector. As in the aforementioned studies, the parameters of the rotation matrix and translation vector can be determined using a numerical search algorithm. Here, instead of a numerical search, we simply considered $(\mathbf{T}_{\text{Shoe},i}^{\text{Global}})^{-1} \mathbf{COP}_i^{\text{Global}}$ and $\mathbf{COP}_i^{\text{Insole}}$ as corresponding clusters of points in different reference frames, and applied a procedure to determine those rigid body transformation parameters in a least-squares sense, using a singular value decomposition [20]. This transformation method is hereafter referred to as RIGID.

Figure 1. Overview of current transformation problem, specifically involving defining a transformation matrix, $\mathbf{T}_{\text{Insole}}^{\text{Shoe}}$ between $(\mathbf{T}_{\text{shoe}}^{\text{Global}})^{-1} \mathbf{COP}^{\text{Global}}$ and $\mathbf{COP}^{\text{Insole}}$. Here, MT1, MT5, and HEEL, respectively, indicate passive reflective markers on the 1st and 5th metatarsal heads and calcaneus. The subscripts Shoe/Global on the axis labels indicate the shoe/global coordinate system.

In the second approach, and without assuming a rigid body transformation, we can consider $\mathbf{T}_{\text{Insole}}^{\text{Shoe}}$ as a function that maps insole pressure measures to $(\mathbf{T}_{\text{shoe},i}^{\text{Global}})^{-1} \mathbf{COP}_i^{\text{Global}}$. Given that a specific functional relationship is unknown, we used a generalized mapping approach, specifically a multilayer, feed-forward neural network (MFNN) with one hidden layer and sigmoid transfer function (see reference [21] for more details). As there are numerous potential ways to define input variables to a MFNN from pressure insole measures, we considered four, simple sets of input variables that could help in selecting input variables for future work (note that each is obtained separately for the two feet):

- **Principal components (PCs) of insole pressure measures, $\mathbf{COP}_i^{\text{Insole}}$:** 99 pressure measures from the insole are converted to forces, and are then divided by half of a participant's body mass. The dimension of these forces is $n \times 99$, where n is the length of each COP time series. To reduce the column dimension, principal component analysis (PCA)—a well-established statistical dimension reduction technique [22]—is performed, and the first PCs that cumulatively explained >90% of variance are selected. The dimension of $\mathbf{COP}^{\text{Insole}}$ is $n \times 2$, excluding Z coordinate data. The MFNN with this set of input variables is referred to as MFNN1.
- **Total force, Ratio of active pressure sensors, $\mathbf{COP}_i^{\text{Insole}}$:** The total force ($n \times 1$ vector) from the pressure insole is divided by half of a participant's body mass. The ratio of active pressure sensors is computed by dividing the number of active pressure sensors (*i.e.*, pressure value > 0) in each time frame by the total number of pressure sensors (*i.e.*, 99). The MFNN with this set of input variables is referred to as MFNN2.
- **Total force, Ratios of active pressure sensors in eight insole regions, $\mathbf{COP}_i^{\text{Insole}}$:** To capture the regional distribution of pressures on the insole, along with the total force described above, the insole is divided into eight regions based on work by Savelberg and de Lange [5]: the lateral and medial parts of the heel, two areas in the mid-foot, three areas in the forefoot, and one area for the toes. The ratio of active pressure sensors in each region is obtained ($n \times 8$), so that the total dimension of input variables becomes $n \times 11$. The MFNN with this set of input variables is referred to as MFNN3.
- **Forces and Ratios of active pressure sensors in eight insole regions, $\mathbf{COP}_i^{\text{Insole}}$:** Both forces and ratios are obtained from the eight noted foot regions (*i.e.*, $n \times 16$), so that the total dimension of input variables becomes $n \times 18$. The MFNN with this set of input variables is referred to as MFNN4.

2.4. Training and Validation of $\mathbf{T}_{\text{Insole}}^{\text{Shoe}}$

For each of the five transformation methods (RIGID, and MFNN1-4), $\mathbf{T}_{\text{Insole}}^{\text{Shoe}}$ was trained and tested using two-fold cross-validation at the participant level. As such, the training and the testing were performed twice, using one replication of simple lifting activities (LL_{GROUND} and LL_{KNUCKLE}), and with the other replication of all MMH tasks for testing. Of note, the simple lifting activities were used for training, since LL_{GROUND} and LL_{KNUCKLE} can respectively represent dynamic and more static activities, and can be easily performed. For the MFNNs, hidden layer sizes from 3–20 were considered during the training, and the final size was selected based on minimizing root mean square (RMS) errors. The final size selected varied from 4–20, depending on participants and foot side. To examine the method validity, three comparative measures were obtained for each MMH task trial, separately in the AP and the ML directions, and in the shoe coordinate system: (1) RMS error (RMSE), where errors were the difference between $\mathbf{COP}_i$ estimated using $\mathbf{T}_{\text{Insole}}^{\text{Shoe}}$ defined by a given method and $(\mathbf{T}_{\text{shoe},i}^{\text{Global}})^{-1} \mathbf{COP}_i^{\text{Global}}$; (2) peak absolute error (PAE); and (3) the coefficient of determination (r^2).

2.5. Statistical Analyses

Separate three-way, repeated measures of analyses of variance (ANOVAs) were performed on the comparative measures, to examine if performance in mapping $\mathbf{COP}^{\text{Insole}}$ to $(\mathbf{T}_{\text{shoe},i}^{\text{Global}})^{-1} \mathbf{COP}_i^{\text{Global}}$ was affected by the four MMH task types (*Task*), foot side (*Foot*; *i.e.*, left vs. right), and the specific method used for $\mathbf{T}_{\text{Insole}}^{\text{Shoe}}$ (*Method*). All comparative measures were log-transformed prior to statistical analyses to achieve normally distributed residuals. Significant effects were examined further using Tukey's HSD *post-hoc* tests. All statistical analyses were complete using JMP® Pro 11.0 (SAS Institute Inc., Cary, NC, USA) with statistical significance determined when $p < 0.05$. All summary data are presented as means (95% Confidence Intervals).

3. Results

A summary of ANOVA results for all comparative measures is presented in Table 1. Only the main and interactive effects of *Task* and *Method* were significant. As shown in Figures 1–3, comparative measures indicated relatively poorer performance during asymmetrical lifting/lowering vs. the other MMH tasks. In addition, for a given task the performance of a MFNN significantly varied depending on input variable sets, and MFNN3 generally outperformed the other MFNN models. Figures 2–4 further highlight that the RIGID method produced comparable results to MFNN3 in some cases. Interestingly, the RIGID method (vs. MFNN methods) yielded significantly higher r^2 values for asymmetrical lifting/lowering.

Table 1. Summary of ANOVA results (F value (p)) for the main and interaction effects of *Task*, *Side*, and *Method* on each comparative measure (significant effects are in bold).

Measure	Task (T) $F_{(3,54)}$	Side (S) $F_{(1,18)}$	Method (M) $F_{(4,72)}$	T × S $F_{(3,54)}$	T × M $F_{(12,216)}$	S × M $F_{(4,72)}$	T × S × M $F_{(12,216)}$
RMSE _{ML}	232.06	0.38	20.61	1.67	4.00	1.05	0.48

	(<0.0001)	(0.54)	(<0.0001)	(0.18)	(<0.0001)	(0.39)	(0.93)
RMSE _{AP}	72.55	0.01	10.97	0.26	8.34	0.26	0.97
	(<0.0001)	(0.93)	(<0.0001)	(0.85)	(<0.0001)	(0.90)	(0.48)
PAE _{ML}	153.77	1.35	9.74	2.61	2.33	1.60	0.34
	(<0.0001)	(0.26)	(<0.0001)	(0.06)	(0.0081)	(0.19)	(0.98)
PAE _{AP}	56.77	0.00	6.85	0.49	5.03	0.15	1.41
	(<0.0001)	(0.99)	(<0.0001)	(0.69)	(<0.0001)	(0.96)	(0.16)
r ² _{ML}	14.53	0.15	3.61	0.79	5.65	0.21	0.82
	(<0.0001)	(0.71)	(0.0097)	(0.51)	(<0.0001)	(0.93)	(0.63)
r ² _{AP}	25.38	0.43	4.00	0.29	3.55	0.81	0.97
	(<0.0001)	(0.52)	(0.0056)	(0.83)	(<0.0001)	(0.52)	(0.48)

Figure 2. Root mean square errors (RMSE) in the antero-posterior (AP: **top**) and the medio-lateral (ML: **bottom**) directions for each MMH task type, with respect to the different methods used for $\mathbf{T}_{\text{Insole}}^{\text{Shoe}}$. Note, see the methods section for detailed descriptions regarding the RIGID and MFNN1–4 methods. Pairs of values with different letters are significantly different within a given MMH task type, and error bars indicate 95% confidence intervals.

Figure 3. Peak absolute errors (PAE) in the AP (**Top**) and the ML (**Bottom**) directions for each MMH task type, with respect to the different methods for $\mathbf{T}_{\text{Insole}}^{\text{Shoe}}$. Pairs of values with different letters are significantly different within a given MMH task type, and error bars indicate 95% confidence intervals.

Figure 4. Coefficients of determination (r^2) in the AP (**Top**) and the ML (**Bottom**) directions for each MMH task type with respect to the different methods for $\mathbf{T}_{\text{Insole}}^{\text{Shoe}}$. Pairs of values with different letters are significantly different within a given MMH task type, and error bars indicate 95% confidence intervals.

4. Discussion

This study examined two different approaches—rigid body transformation, and nonlinear mapping (MFNN)—to define a transformation between the coordinate systems of an IPM and the shoe itself (the latter being essentially equivalent to the global, or motion capture, coordinate system). Performance of the two approaches was assessed during several MMH activities. Overall, the results indicated that: (1) performance varied between MMH activity types regardless of the specific approach used; and (2) a MFNN performed better than or comparable to the rigid body transformation approach, depending on the specific input variable sets used.

The performance of the different transformation methods to define $\mathbf{T}_{\text{Insole}}^{\text{Shoe}}$ varied with the MMH activity types. For example, asymmetric lifting resulted typically in larger errors and smaller r^2 values than the other activities (Figures 2–4). In the case of LL_{GROUND}, LL_{KNUCKLE}, and PushPull, mean RMSE values ranged from 6.5/2.3 mm–16.6/6.8 mm in the AP/ML directions, depending on the transformation methods. Such errors are of similar magnitude to errors obtained during gait in earlier studies, which have reported mean RMSE values of 6.1/1.3 mm–13.7/7.3 mm in the AP/ML directions [10,17,18]. Chumanov *et al.* [17] and Fradet *et al.* [15] highlighted that relatively larger errors are obtained during the toe-off and/or the heel-strike phase of gait, and Fradet *et al.*, further indicated that a potential error source is the deformation of shoes and insoles at these gait phases. The relatively poorer performance observed here for LL_{ASYM}, therefore, could be explained by the fact that LL_{ASYM} requires more complex foot movements (e.g., turning, rolling, *etc.*) than the other activities. In addition, training for $\mathbf{T}_{\text{Insole}}^{\text{Shoe}}$ was completed using only simple lifting activities (LL_{GROUND} and LL_{KNUCKLE}), and which also likely contributed to a poorer performance for LL_{ASYM}.

Use of a rigid body assumption to define the relationship between the insole and the shoe coordinate system may not be strictly valid, for at least two reasons. First, following the two-fold cross-validation, the rigid body transformation matrix was defined with one replication of LL_{GROUND} and LL_{KNUCKLE}, and tested with the other replication of all MMH activities. Therefore, if the rigid body assumption is strictly valid, fairly good performance of $\mathbf{T}_{\text{Insole}}^{\text{Shoe}}$ can be expected at least for LL_{GROUND} and LL_{KNUCKLE}, even though the insole captures only compressive forces (while the force platform captures tri-axial forces) and the foot may move inside the shoe during the MMH activities. LL_{GROUND} and LL_{KNUCKLE}, however, yielded RMSE and PAE values similar to PushPull (Figures 2,3), and smaller values of r^2 in the ML direction than PushPull (Figure 4). In this study, all participants wore their own athletic shoes during data collection. An athletic shoe insole is pliant and soft, providing underfoot cushioning. Such a shoe insole could thus deform to varying degrees, depending on in-shoe foot loading patterns. This deformation may weaken the rigid body assumption for $\mathbf{T}_{\text{Insole}}^{\text{Shoe}}$. Second, two of the nonlinear mapping functions used here (*i.e.*, MFNN3 and MFNN4) typically performed better than or comparable to the rigid body transformation matrix (though with some exceptions such as r^2 values for LL_{ASYM}). Recall that MFNN3 and MFNN4 used the ratios of active pressure sensors in the eight regions as part of the

input variables, and information on such ratios likely reflected in-shoe foot loading patterns. It can thus be argued that MFNN3 and MFNN4 were trained to account, to some degree, for potential shoe insole deformation during the MMH activities.

Our study has some limitations of note. The MMH activities were performed in a laboratory environment, on a flat and regular surface. Irregularity of the ground surface will influence interactions between the shoe and the floor, and subsequently the degree of shoe deformation. Thus, future work is needed to assess IPM systems on under more general environmental conditions. In addition, the current sample size was somewhat small (*i.e.*, 10 participants). Though our results provided some direction for defining $\mathbf{T}_{\text{Insole}}^{\text{Shoe}}$, future work is also needed to consider more diverse populations (e.g., with obesity, foot deformities, *etc.*) for the rigid body transformation and nonlinear mapping approaches, so as to understand the generalizability of these approaches.

5. Conclusions/Outlook

Two different approaches—rigid body transformation, and nonlinear mapping—were examined to define a relationship between the insole and the shoe coordinate system, $\mathbf{T}_{\text{Insole}}^{\text{Shoe}}$, and the performance of the two approaches were examined during several MMH activities. MMH activity types affected the performance of the two approaches, with an asymmetric task (LL_{ASYM}) yielding relatively poorer performance. The latter was attributed to potential shoe and insole deformations during LL_{ASYM}. We further argued that the rigid body assumption to define a relationship between the insole and the shoe coordinate system may not be strictly valid, and suggested that a nonlinear mapping approach could account for potential shoe insole deformation during activities. Though our focus was MMH activities, a nonlinear mapping approach may also be effective in investigating postural balance during functional ambulation, since ambulatory activities such as stair climbing/descending likely induce shoe insole deformation. Existing studies using an IS (instrumented shoe) system [8,23] have reported mean RMSE errors or average absolute errors of <10 mm, and which is less than current errors since an IS system directly captures forces between the shoe (with externally attached tri-axial transducers) and the floor. Therefore, more efforts are needed to improve the performance of the methods to define $\mathbf{T}_{\text{Insole}}^{\text{Shoe}}$ (e.g., incorporating foot kinematics along with IPM data, solving a transformation matrix, $\mathbf{T}_{\text{Insole}}^{\text{Shoe}}$ without considering it homogeneous as in [20], *etc.*). In addition, and as noted in the limitations above, future work should examine the performance of methods to define $\mathbf{T}_{\text{Insole}}^{\text{Shoe}}$ on different surfaces and/or with larger and more diverse populations.

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4.3. Classification of manual tasks based on data from wearable sensors

Kim S, Nussbaum MA: [2014] An evaluation of methods to classify manual material handling tasks from data obtained using wearable technologies. *Ergonomics* 57:1040-1051.

Abstract

With recent progress in wearable measurement systems physical exposures can be feasibly assessed at high precision in the workplace. Such systems, however, generally lack contextual information for a given job (e.g., task type, duration). To extract such information, we explored three classification algorithms to classify manual material handling (MMH) tasks during a simulated job in a laboratory, using several combinations of outputs from commercially-available inertial motion capture and in-shoe pressure measurement systems. Ten participants completed three replications of four cycles of a simulated job. Precision and recall values of $\geq \sim 90\%$ and 80% , respectively, and errors in estimated task duration of $< \sim 14\%$, could be achieved across the MMH task examined. Classification performance, however, varied between classification algorithms, input data sets, and task types. Overall, combining wearable technology with task classification could be an effective approach for field-based exposure assessment, though field-testing is needed to demonstrate the applicability of this method.

1. Introduction

Work-related musculoskeletal disorders (WMDs) are an important issue in the workplace, as they account for $\sim 30\%$ of all lost work days (BLS, 2011; 2012) and involve substantial associated costs (Liberty Mutual, 2012). To prevent and control such disorders, an effective approach to assess physical exposures (e.g., postures, joint forces and moments) is often needed for research and practice. Quantifying physical exposures can help identify high-risk work conditions, understand relationships between exposures and health outcomes, and aid in the design and evaluation of ergonomic interventions (Burdorf et al., 1997; Lötters & Burdorf, 2002; Westgaard & Winkel, 1997). However, the way in which a worker interacts with tasks and work conditions (e.g., work process/cycles, physical constraints) influences the level of physical exposures imposed. Such interactions could be distinct for an individual or group of workers and change over time, and thus exposure assessment is ideally performed in a real work environment vs. in a simulated laboratory setting. Recently, the need for research in more realistic and applied settings has been emphasized by some authors (e.g., Chung & Shorrock, 2011; Neumann, et al., 2012). Developing accurate and detailed field-based physical exposure assessment methods, however, has been an ongoing challenge (Garg & Kapellusch, 2009; Marras et al., 2009; Waters et al., 2007).

Recent developments in wearable measurement systems can facilitate monitoring of body motions and external forces *in situ*. For example, detailed body segment kinematics can potentially be assessed during occupational tasks using inertial measurement units (IMUs; Godwin et al., 2009; Kim & Nussbaum, 2013; Plamondon et al., 2007). Further, ground reaction forces and moments can be estimated using in-shoe pressure measurement (IPM) systems

(Forner-Cordero et al., 2004; Savelberg & de Lange, 1999) and instrumented shoes (Faber et al., 2010; Veltink et al., 2005). Information yielded by such measurement systems appears to be numerically detailed and accurate in many cases. Lacking from those systems, however, is direct contextual information for a given job – specifically, what tasks are performed, when, where, how frequently and/or how long, etc. – though information on job-specific contexts is needed to effectively address real-world ergonomics problems (Chung & Shorrock, 2011; Neumann et al., 2012). To address this need, some previous authors have suggested using both an observational method and a direct measurement system as an improved approach for comprehensive assessments of physical exposures (Juul-Kristensen et al., 2001; Teschke et al., 2009; Wells et al., 1994). Using both systems, though, is more costly, time consuming, and resource-demanding than using either alone. Continuous observation of postures, in particular, is quite labor intensive (Rezaghali et al., 2012; Trask et al., 2007), and the quality of such observation can be affected by the training and experience of observers (Denis et al., 2002; Weir et al., 2011). Maintaining a clear and unobstructed view within a reasonable distance can also be a practical concern with observations on site or using videos.

Extracting exposure contexts (e.g., task type, duration) can be viewed as a form of task classification, involving (ideally) automatic recognition of the different tasks that an individual performs. Though largely in the fields of healthcare-related research and pervasive computing, different types of wearable sensors (e.g., accelerometers, IMUs, IPMs) have been used, with many promising results, to classify daily tasks (Altun et al., 2010; Blanke & Schiele, 2009; Pärkkä et al., 2006; Zhao et al., 2010) and manufacturing assembly tasks (Ogris et al., 2011; Stiefmeier et al., 2006). In these and related studies, a research focus often has been on recognizing semantically-meaningful (i.e., high-level) behaviors. Manual material handling (MMH) tasks also can be seen as high-level behaviors involving interactions with an object, suggesting that task classification could identify MMH tasks performed by an individual worker. In summary, combining the detailed (but often extensive) data obtainable from wearable technologies with task classification can possibly facilitate the collection of both numerically- and contextually-rich information regarding a job, in the field, and with (ideally) minimal efforts. Therefore, this may be an important physical exposure assessment approach.

The current study was aimed at examining the potential of using commercially-available wearable measurement systems [inertial motion capture (IMC) and IPM] to classify MMH tasks during a simulated job. Note that this study only targeted MMH tasks, since these are a well-documented risk factor for WMSDs (NRC, 2001). A commercial IMC system typically includes a set of IMUs that can be placed on multiple body parts depending on the number of available IMUs and the number of workers to monitor. We therefore explored different combinations of IMU and/or IPM output time series, and these served as inputs for assessing different conventional classification algorithms (linear discriminant analysis, *k*-nearest neighbor, and multi-layer feedforward neural network). Three distinct algorithms were tested, since, as noted in recent reviews on classification methods (Jain et al., 2000; Preece et al., 2009), no single optimal solution exists for all classification problems. The performance of the three algorithms was compared for the different sensor output combinations and task type, in terms of MMH-task classification ability – specifically, precision, recall, and the estimated time duration of a task classified (i.e., information on how long a worker performs each of the tasks in a given job). As

this study was more exploratory and data-driven in nature, no *a priori* hypotheses were formulated.

2. Methods

Ten healthy, young volunteers (19-29 years old, 5 males and 5 females) from the local university and community completed the study. Their mean (SD: range) stature, body mass, and foot length were 171.5 (6.9: 164-183) cm, 76.1 (13.2: 62.5-104.6) kg, and 26.8 (1.5: 24.5-29) cm, respectively. All participants reported being moderately physically active and having no musculoskeletal injuries limiting normal daily activities within the past year. Prior to any data collection, participants completed an informed consent procedure approved by the Virginia Tech Institutional Review Board.

2.1 Experimental procedures and instrumentation

Participants performed four cycles of a simulated job a total of three times. Each cycle was comprised of a set of six MMH activities, and was designed to include several major types of MMH tasks (i.e., lifting/lowering, pushing/pulling, and carrying). The specific MMH activities were as follows (see also Figure 1):

- Activity 1: carry the box to a table (i.e., symmetric lifting, carrying, and lowering to knuckle height).
- Activity 2: transfer the box from one table to another (i.e., asymmetric lifting).
- Activity 3: carry the box from one table to another (i.e., lifting from knuckle height, carrying and lowering to knuckle height).
- Activity 4: push the box away from the body (distance = ~70 cm).
- Activity 5: pull the box toward the body (distance = ~70 cm).
- Activity 6: place the box from a table onto the ground (i.e., lifting from knuckle height, carrying, and lowering to the ground).
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Figure 1. Illustrations of the simulated job (Left), involving six MMH activities, and the relevant dimensions (Right). Dotted lines indicate the clockwise movement path. The red rectangular zones (A, B, and C) indicate three different starting locations for a job cycle.

Participants completed four cycles of the simulated job from a given starting location (Figure 1). Three total replications were completed (i.e., three groups of four cycles), with each replication beginning a job cycle from one of the three different starting locations. The presentation order of starting location was randomized for each participant, and within starting location the work direction (i.e., clockwise vs. counterclockwise) was also randomly assigned. Participants were asked to complete each activity using self-selected comfortable styles and speeds, but within 15 sec. The beginning of each cycle and discrete activity was paced with computer-generated auditory tones, and 30 sec. of rest was given between cycles. Each replication of four job

cycles lasted 7 min, and 3 min. of rest was given after each cycle. Note that participants were allowed to change their working styles and speed as desired, as well as to move freely during the rest periods.

Whole-body kinematics were monitored using an IMC system (MVN BIOMECH, Xsens technologies B.V., Enschede, the Netherlands) with 17 IMUs positioned on the head, sternum and pelvis; and bilaterally on the scapulae, the upper and lower arms, hands, thighs, shanks, and feet (see www.xsens.com/en/mvn-biomech for additional details). Ground reaction forces were obtained using an IPM system (Pedar™, Novel GmbH, Munich, Germany) with 99 pressure sensors in each of two insoles. Both systems were sampled at 60 Hz. To synchronize the systems, one reflective marker was placed on the heel of one foot, monitored using a 7-camera optical motion capture system (Vicon MX, Vicon Motion Systems Inc., Denver, CO, US). Participants were then asked to perform an easily identifiable movement at the start of each replication (i.e., quickly raising a foot). The IPM system was synchronized with the other systems via a TTL pulse (Pedar™ Sync Box). All off-line data processing was completed using Matlab 7 (Mathwork™ Inc., Natick, MA, US).

2.2 MMH task classification

Given the large number of possibilities for different measurement unit configurations, seven different input data sets were defined by separately combining body joint angles that can describe the whole, the upper or the lower body, with and without IPM data, and these sets were intended to represent a range of possible applications. The seven input sets consisted of different combinations of IMC and/or IPM output time series:

- Pelvis angles with IPM data (PELV+IPM): pelvis angles were the flexion/extension and lateral bending angles. Two sets of pressure data (i.e., 99 pressure sensors from each foot) were included. Pressure data were normalized to the product of body mass and foot area, similar to Rouhani et al. (2010). Thus, each frame of data was a 200-dimensional vector, including normalized pressure data.
- Lower body joint angles with IPM data (LB+IPM): lower body joint angles were the sagittal and frontal plane rotation angles of the pelvis, bilateral 3-D direct cosine angles of the upper leg, and bilateral 1-D included knee joint angles. Each frame of data was a 208-dimensional vector, including normalized pressure data.
- Upper body joint angles with IPM data (UB+IPM): upper body joint angles were the flexion/extension and lateral bending angles of the pelvis, 3-D trunk angles, bilateral 3-D direct cosine angles of the upper arm, and bilateral 1-D elbow joint included angles. Each frame of data was a 211-dimensional vector, including normalized pressure data.
- Whole body joint angles (WB_{ANG}): flexion/extension and lateral bending angles of the pelvis (respectively determined relative to the gravitational vector and the ground), 3-D trunk angles relative to the pelvis, bilateral 3-D direct cosine angles of the upper arm relative to the trunk, bilateral 1-D elbow joint included angles (i.e., flexion-extension), bilateral 3-D direct cosine angles of the upper leg relative to the pelvis, and bilateral 1-D included knee joint angles (i.e., flexion-extension). Thus, each frame of data was a 21-dimensional vector.
- Whole body joint angles and angular velocities ($WB_{ANG+VEL}$): whole body joint angles and their time derivatives were included. Each frame of data was a 42-dimensional vector.

- Whole body joint angles and IPM data ($WB_{ANG}+IPM$): whole body joint angles and normalized pressure data were included. Each frame of data was a 219-dimensional vector.
- Whole body joint angles, angular velocities and IPM data ($WB_{ANG+VEL}+IPM$): whole body joint angles, angular velocities and normalized pressure data were included. Each frame of data was a 240-dimensional vector.

Task classification was performed for each participant, using each of the seven input data sets above. Conceptually, this task classification was conducted to identify, from a time series of data, what tasks were being done and when. Figure 2 provides an overview of the processes involved in MMH task classification, and each process is described in more detail below. In the current study, eight MMH tasks involved in one or more of the six MMH activities were of primary interest for classification: 1) lifting from the ground ($Lifting_{GROUND}$), 2) lifting from knuckle height ($Lifting_{KNUCKLE}$), 3) lowering to the ground ($Lowering_{GROUND}$), 4) lowering to knuckle height ($Lowering_{KNUCKLE}$), 5) pushing, 6) pulling, 7) carrying, and 8) walking (only as required to perform the activities).

Figure 2. An overview of the process of MMH task classification for each participant.

2.2.1 Quantizing times series of input data sets

An unsupervised clustering algorithm can be used to explore hidden structures in a set of data, and such structures can enable a reliable identification of tasks with a subsequent supervised task classification algorithm (Preece et al., 2009). A self-organizing map (SOM) is a neural network based on an unsupervised clustering algorithm (Kohonen, 1990). Here, an SOM was constructed with 1024 neurons in a 32 x 32 hexagonal grid [using the SOM Toolbox (Vesanto et al., 1999)], and which was used to cluster the time series of an input data set. Then, each frame of the time series was replaced with a corresponding cluster centroid vector – of the same dimension as the input data set – from the SOM.

2.2.2 Feature extraction and data reduction

Feature extraction is a typical pre-processing step for characterizing time series using, for example, descriptive statistics, fast Fourier transform components, etc. (Preece et al., 2009). Extracted features are then used as inputs to classification algorithms. Here, to extract statistical features, a sliding window of size 10 frames (0.17 sec.) was moved over each time series vector of the input data set with 50% overlap. In each window, five descriptive statistics were obtained: mean, variance, min, max, and kurtosis. Therefore, for example, each frame of the WB_{ANG} data set became a 105-dimensional feature vector (5×21), and the time series length was reduced by one fifth. For data sets including IPM outputs, the dimension of a feature vector became rather large (≥ 495). In these cases, principal component analysis (PCA), a well-established statistical dimension reduction technique (Jolliffe, 2002), was performed to reduce the dimensions of a feature vector. The first 150 PCs were found to explain >99.5% of the

variance in the datasets for each participant, so that the dimension of a feature vector for all data sets including IPM data was reduced to 150 (from ≥ 495).

2.2.3 Classification algorithms

Three different conventional classification algorithms were used to classify the MMH tasks. A brief description of each algorithm is provided below, along with references for additional information. The three classification algorithms are:

- Linear discriminant analysis (LDA): a representative subspace analysis technique, used to find discriminant functions that maximize the ratio of between-class separability vs. within-class variability (Webb & Copsey, 2011).
- k -nearest neighbor (k -NN): a widely-used distance-based technique, which assigns an unclassified input vector to the nearest known class (Webb & Copsey, 2011). Selecting the number of nearest neighbors, k , is typically exploratory; here, k -NN was performed with both $k = 3$ and 5.
- Multilayer feedforward neural network (MFNN): at a simplified level, a MFNN is a nonlinear mapping structure that typically consists of input, hidden, and output layer of “neurons”, with transfer functions between layers. Inter-connections, or weights, between neurons are determined for a given data set through a “learning” process (Bishop, 1995; Haykin, 1999). Here, a MFNN was developed with sigmoid transfer functions, and with the size of one hidden layer set to both 20 and 30.

Each MMH classifier was trained and tested with each of the seven input data sets, using 3-fold cross-validation. As such, and for each participant, training and testing were performed three times, using two replications of the MMH tasks for training and the remaining replication for testing. Of note, the 3-NN and the MFNN with hidden layer size = 20 (MFNN20) respectively performed similarly to the 5-NN and the MFNN30 (Kim, 2012); thus, results using only the latter classifiers is reported. Examples of classification outputs are presented in Figures 3 and 4.

Figure 3. An example of classification outputs using the $WB_{ANG+VEL}$ data set (whole body joint angles and angular velocities). Classification algorithms used here were linear discriminant analysis (LDA) and multilayer feedforward neural network with the hidden layer size = 30 (MFNN30). The vertical axis shows eight tasks classified, and horizontal lines indicate tasks performed or identified.

Figure 4. An example of classification outputs for Lifting from the ground (Lifting_{GROUND}), using the WB_{ANG+VEL} data set. Note that Lifting_{KNUCKLE} is Lifting from knuckle height, and NC stands for Not Classified (indicating that a given input vector was not classified into any of the eight MMH tasks).

The performance of the different MMH-task classifiers was assessed using two common measures (Fawcett, 2004) – *precision* and *recall* (or sensitivity). Precision is the percentage of cases that a task is correctly classified [i.e., positive predictive value = true positives / (true positives + false positives)], and recall is the percentage of cases that a task is correctly classified (i.e., true positive rate = true positive / total positives). In addition, the time durations of each MMH tasks were estimated for each replication of four cycles, using select input data sets that yielded different performance levels, to examine their ability to summarize a given job in terms of the task durations that an individual worker performed. A percentage error was then calculated, comparing these estimates to actual (aka “ground truth”) time durations determined by direct observation (using video recordings).

3. Statistical analyses

Three-way repeated-measures analyses of variances (RANOVAs) were performed to assess the main and interactive effects of input data sets (*Data set*), MMH-task classifiers (*Classifier*), and MMH tasks (*Task*) on precision and recall values. Where relevant, post-hoc comparisons were conducted using Tukey’s Honestly Significant Difference (HSD) tests. Given the extent of analyses obtained, interpretation of statistical results focuses on the predominant emerging patterns in classification performance, with respect to *Data set*, *Classifier*, and *Task*, rather than on specific differences across the levels of independent variables. In addition, the percentage errors in the time proportions of MMH tasks estimated vs. “ground truth” are summarized. All statistical analyses were completed using JMP 9.0 (SAS Institute Inc., Cary, NC, USA) with statistical significance determined when $p < 0.05$. All summary data are presented as means (SD).

4. Results

All main and interaction effects of *Data set*, *Classifier*, and *Task* were significant on precision and recall (all p values ≤ 0.0002), except that the second-order interaction effect was not significant for precision ($p = 0.23$). A summary of precision and recall values is illustrated in Figures 5 and 6, in which it is evident that task classification performance varied substantially with classifiers, input data sets, and/or MMH tasks. The LDA and 5-NN classifiers appeared to perform similarly, and substantially better than the MFNN classifier for some task types – Lifting_{GROUND}, Lowering_{GROUND}, Lowering_{KNUCKLE}, Pushing and Pulling. Four particular input data sets (UB+IPM, WB_{ANG}+IPM, WB_{ANG+VEL} and WB_{ANG+VEL}+IPM) had comparable and relatively better performance than the remaining input data sets, though these three input data sets

yielded different levels of performance depending on classifiers and task types. Further, PELV+IMP typically resulted in the worst performance. Using the respective best combinations of input data set and MMH-task classifier for each task, median values (across participants) of the highest precision/recall values achieved for each task type were: 99%/80% for Lifting_{GROUND}, 90%/86% for Lifting_{KNUCKLE}, 98%/83% for Lowering_{GROUND}, 90%/81% for Lowering_{KNUCKLE}, 97%/93% for Pushing, 97%/93% for Pulling, 93%/97% for Carrying and 95%/90% for Walking.

Figure 5. Precision plot for each input data set, MMH-task classifier, and task type. See Methods for detailed descriptions of the input data sets (PELV+IPM, LB+IPM, UB+IPM, WB_{ANG}, WB_{ANG}+IPM, WB_{ANG}+VEL, and WB_{ANG}+VEL+IPM). LDA is linear discriminant analysis, 5-NN is 5-nearest neighbor, and MFNN30 s multilayer feedforward neural networks with hidden layer size = 30. Note that whiskers on the box plots indicate the lowest and highest values within the 1.5 × interquartile range.

Figure 6. Recall plot for each input data set, MMH-task classifier, and task type. See Methods for detailed descriptions of the input data sets (PELV+IPM, LB+IPM, UB+IPM, WB_{ANG}, WB_{ANG}+IPM, WB_{ANG}+VEL, and WB_{ANG}+VEL+IPM). LDA is linear discriminant analysis, 5-NN is 5-nearest neighbor, and MFNN30 s multilayer feedforward neural networks with hidden layer size = 30. Note that whiskers on the box plots indicate the lowest and highest values within the 1.5 × interquartile range.

Percentage errors in the time durations of MMH tasks are summarized in Table 1, for four select input data sets (PELV+IPM, WB_{ANG}+IPM, WB_{ANG}+VEL and WB_{ANG}+VEL+IPM) with LDA, 5-NN and MFNN30 classifiers. Note, these input data sets were to represent a range of different performance levels. The time duration estimated by a classifier was typically shorter than “ground truth”, by ~1% to ~89%.

Table 1. Summary [median (interquartile range = 3rd quartile – 1st quartile)] of actual (“ground truth”) time durations from direct observation within each replication, and percentage errors in time durations of MMH tasks estimated using the MMH task classifiers. A negative value indicates that the classifier underestimated duration. Note that LDA, 5-NN and MFNN30 respectively indicate linear discriminant analysis, 5-nearest neighbor, multilayer feedforward neural network with the hidden layer size = 30. The PELV+IPM input data set is IPM pressure data, WB_{ANG}+IPM is whole body joint angles and IPM pressure data, and WB_{ANG}+VEL data set is whole body joint angles and angular velocities, and WB_{ANG}+VEL+IPM is whole body joint angles, angular velocities and IPM pressure data.

	L _{GROUND}	L _{KNUCKLE}	LW _{GROUND}	LW _{KNUCKLE}	Pushing	Pulling	Carrying	Walking

Ground Truth Time Duration (sec.)		10.5 (1.6)	28.9(4.0)	12.3 (1.7)	20.9 (7.8)	11.7 (1.6)	13.4 (2.9)	27.0 (4.1)	44.6 (9.7)
LDA	PELV+IPM	-49.2 (32.8)	-42.9 (28.6)	-54.6 (36.0)	-49.8 (32.8)	-42.3 (55.0)	-30.9 (48.0)	-12.4 (49.0)	-15.5 (47.3)
	WB _{ANG} +IPM	-23.6 (13.8)	-1.7 (22.2)	-15.3 (19.2)	-8.5 (22.3)	-9.3 (18.8)	-8.4 (26.3)	2.2 (18.2)	-11.4 (24.6)
	WB _{ANG} +VEL	-17.6 (20.0)	0.0 (26.7)	-4.9 (19.0)	-1.3 (34.9)	-15.2 (13.9)	-11.3 (11.6)	3.3 (15.0)	-6.4 (20.3)
	WB _{ANG} +VEL+IPM	-13.7 (16.1)	-3.0 (17.3)	-3.8 (16.4)	-1.5 (19.5)	-13.7 (15.2)	-7.1 (12.3)	0.4 (12.9)	-6.8 (19.1)
5-NN	PELV+IPM	-56.6 (34.7)	-64.7 (20.1)	-63.7 (28.3)	-61.2 (31.9)	-50.0 (56.0)	-42.6 (48.0)	-5.3 (55.2)	-29.1 (37.6)
	WB _{ANG} +IPM	-23.9 (19.5)	-19.4 (19.4)	-19.4 (14.5)	-22.2 (22.1)	-10.6 (17.4)	-6.2 (21.6)	-2.0 (20.1)	-22.6 (20.5)
	WB _{ANG} +VEL	-15.4 (25.9)	-4.7 (20.3)	-2.8 (14.7)	-9.2 (24.5)	-4.1 (11.0)	-2.1 (15.1)	3.9 (18.3)	-9.6 (17.8)
	WB _{ANG} +VEL+IPM	-14.0 (22.4)	-3.4 (18.7)	-4.8 (13.9)	-8.4 (20.1)	-4.7 (16.1)	-1.3 (17.8)	1.2 (20.7)	-13.8 (17.7)
MFNN30	PELV+IPM	-52.1 (43.4)	-50.5 (34.4)	-57.4 (41.8)	-40.0 (35.1)	-71.4 (32.3)	-89.8 (66.1)	-22.2 (46.4)	-15.8 (32.9)
	WB _{ANG} +IPM	-46.5 (55.9)	0.5 (21.6)	-20.5 (29.6)	-16.0 (28.0)	-50.3 (81.5)	-27.8 (4.34)	5.0 (30.2)	-10.9 (20.6)
	WB _{ANG} +VEL	-16.0 (28.0)	12.4 (45.2)	-7.8 (29.6)	-1.8 (54.7)	-34.3 (85.3)	-4.7 (53.9)	7.7 (17.1)	-6.7 (14.0)
	WB _{ANG} +VEL+IPM	-15.6 (21.4)	-5.2 (21.0)	-11.1 (31.2)	-1.3 (23.1)	-13.1 (19.4)	-3.3 (23.0)	6.0 (17.8)	-8.8 (21.8)

5. Discussion

Combining wearable technology with task classification could serve as an effective field-based exposure assessment approach, in that this combination can provide both numerically-detailed and contextually-rich information about a job. The current analysis explored the ability to achieve manual material task classification using data obtained from two commercial wearable measurement systems. Specifically, this classification was employed to extract contextual information (i.e., task types and their time proportions) during a simulated job. Three different MMH-task classifiers were developed to automatically classify MMH tasks, and each was used with seven different combinations of IMU and/or IPM time series as inputs. For all task types, median values of precision and recall achieved levels $\geq \sim 90$ and 80% , respectively, when using the best combinations of input data sets and classifiers, and mean error in estimated MMH task duration was $< \sim 14\%$ (Table 1).

Task classification performance and duration estimation varied, however, and in some cases substantially, depending on the specific classification algorithms, input data sets, or task type (Figure 5 and 6). Similar dependency of task classification has been shown in previous studies (Altun & Barshan, 2010; Blanke & Schiele, 2009; Gyllenstein & Bonomi, 2011; Ogris et al., 2008; Pärkkä et al., 2006), which reported classification precision of ~ 30 to $\sim 99\%$. In these, lower precision was generally associated with tasks involving a larger degree of movement variability and/or less distinct motion characteristics (e.g., opening door, preparing food), and also tasks performed in a less controlled environment (e.g., real-life scenarios). van Hees et al. (2013) further noted that the performance of a task classifier can be overestimated with *controlled* laboratory studies. While the use of job simulation here, conducted in a laboratory setting, represents a potential limitation to external validity, minimal control was imposed in that participants could change their working styles and move freely during rest periods. In addition, our results suggest that the current MMH-task classifier had trouble correctly identifying the beginning and ending times of a task (see Figure 4 as example); this explains, at least in part, the shorter task time durations estimated compared to “ground truth” durations (Table 1). When using observational physical exposure assessment methods, defining such “ground truth” for body motions is difficult (Takala et al., 2010), and continuous observation is labor-intensive (van der Beek & Frings-Dresen, 1998). Such challenges could be addressed using an MMH-task classifier, though further improvements are needed for better estimations of task duration. The use of portable measurement systems with task classification should be examined in diverse actual work environments. However, the current results regarding MMH-task classification

performance, overall, support the potential of the proposed approach as a field-based exposure assessment, and offer some indication of the limits of outputs obtained (i.e., regarding precision, recall, and estimated task duration).

The current results can also be used to provide practical guidance on selecting input data sets for MMH-task classification. First, when the number of IMUs is limited, tracking upper (vs. lower) body joint kinematics yielded better classification performance for the MMH tasks (see Figures 5 and 6). In fact, upper body joint angles with IPM data (UB+IPM) resulted in similar or better classification performance than whole body joint angles with IPM data (WB+IPM), as shown in Table 1. Upper (vs. lower) body joint kinematics thus could be viewed to having more discriminative information, likely because each of the current MMH tasks involved more distinct upper body movements than lower body movements (e.g., pulling vs. pushing). A recent comprehensive study on sensor placing for activity classification (Atallah et al., 2011) similarly indicated that an optimal sensor location is associated with the movement characteristics (e.g., dominant or principal moving body parts) of an activity. Second, a comparison between WB_{ANG} and $WB_{ANG+VEL}$ input sets showed that $WB_{ANG+VEL}$ resulted in up to a ~24% performance gain in precision and/or recall, suggesting that incorporating information on angular velocities is of value for improving classification performance. Third, inclusion of IPM data, as input for classification, appears relevant for MMH-task classification only when sufficient body kinematic information is also available as part of the input data. Though not examined here, and requiring future assessment, it is possible that IPM data could provide discriminative information to distinguish loaded vs. unloaded motions, or even the magnitude of a load handled during MMH tasks.

The current study was exploratory in nature, and there are likely several directions for improving the performance of MMH-task classifiers. As reviewed in detail elsewhere (Jain et al., 2000; Preece et al., 2009), specific feature extraction and selection methods can substantially affect classification performance. While we used several descriptive statistics to characterize input data in a sliding window, more informative features could be derived from the frequency or time-frequency domain, respectively using fast Fourier transformation or wavelet analysis. With IPM data included as an input to a classifier, we used PCA to select a subset of the features, yet an optimal set of features could be selected more rigorously using heuristic approaches such as forward/backward sequential selection (Dash & Liu, 1997) or mutual-information-based feature selection (Peng et al., 2005). Further, future work should explore whether classification performance can be improved by combining the current input data (or a subset thereof) with additional information (e.g., acceleration). Though our results suggested that LDA and k -NN are reasonable base classification algorithms for recognizing MMH tasks, different classification algorithms – such as Bayesian decision-making, support vector machines, and hidden Markov models – could be explored. Though these algorithms do not necessarily generate better classification performance, some previous studies (Peng et al., 2005; Tunçel et al., 2009; Wang et al., 2011) have reported that such algorithms can, in some cases, outperform the types of algorithms examined here. Moreover, classification algorithms could be implemented for real-time processing, to enable potentially broader application of wearable systems in exposure assessment. Vignais et al. (2013), for example, explored using a set of IMUs to obtain a Rapid

Upper Limb Assessment (RULA) index in real time during simulated manufacturing tasks, and using this to provide a worker with auditory feedback when the demand was high.

This study used two commercial wearable systems to classify MMH tasks during a simulated job, to assess this approach as a potential field-based exposure assessment method. The results indicated that precision and recall values of $\geq \sim 90\%$ and 80% could be achieved across the MMH task examined. Task classification performance, however, varied with classification algorithms, input data sets, and task types. Task durations were typically underestimated ($\sim 14\%$). For practical application, upper rather than lower body joint kinematics appear to have more discriminant information, joint angular velocities may help with classification performance, and IPM data may be of benefit only along with IMU input. Further, LDA and k -NN appear to be effective choices for base classification algorithms. While the current results support the potential of the current approach for field-based exposure assessment, future work is needed in several directions. Such future work should examine alternative classification methods; evaluate wearable systems with task classification in diverse, real work environments, wherein the performance of a MMH classifier might be potentially compromised due to the existence of “untrained” tasks; and also develop and evaluate MMH-task classifiers at the population level (vs. individual level here), to facilitate more efficient use of wearable systems with task classification in exposure assessment.

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4.4. Enhanced task classification methods using wearable-sensor data

Bastani K, Kim S, Kong Z, Nussbaum MA, Huang W, Zhou Y: Online classification and sensor selection optimization with applications to human manual material handling tasks using wearable sensing technologies. Submitted to the IEEE Transactions on Human Machine Systems.

Abstract

Occupational jobs often involve different types of manual material handling (MMH) tasks. Performing such tasks can be physically demanding, and which may put workers at high risk of work-related musculoskeletal disorders (WMSDs). To control and prevent WMSDs, there has been recently a growing interest in online posture monitoring using wearable sensors. In this paper, we developed an online supervised classification algorithm for monitoring and evaluation of MMH tasks. The classification algorithm is based on a fast sparse estimation methodology, which makes it computationally efficient for online decision making. We further propose an optimization approach to improve the classification performance, by assigning different weights to sensors. Each weight represents the importance level of a sensor in classification performance. As such, optimizing these weights enables us to determine the most relevant sensors for classification. The case study using 37 sensors with 111 channels of data was performed to validate the performance of the proposed method. The results showed that with only 30 optimally selected sensor channels, our method can still provide high classification accuracy (>84%), and outperforms the benchmark methods, including support vector machine, quadratic discriminant analysis, neural network, etc.

LIST OF PUBLICATIONS

The following lists publications that have resulted to date from work supported (directly or indirectly) by this grant, and a list of future publications that are anticipated.

Journal Articles

1. Jia B, Kim S, Nussbaum MA: [2011] An EMG-based model to estimate lumbar muscle forces and spinal loads during complex, high-effort tasks: development and application to residential construction using prefabricated walls. *International Journal of Industrial Ergonomics* 41:437-446.
2. Kim S, Nussbaum MA, Jia, B: [2011] Low back injury risks during construction with prefabricated (panelised) walls: effects of task and design factors. *Ergonomics* 54:60-71.
3. Kim S, Nussbaum MA, Jia B: [2012] The benefits of an additional worker are task-dependent: assessing low-back injury risks during prefabricated (panelized) wall construction. *Applied Ergonomics* 43:843-849.
4. Shewchuk J, Guo C: [2012] Panel stacking, panel sequencing, and stack locating in residential construction: lean approach, *Journal of Construction Engineering and Management* 138:1006-1016.
5. Kim S, Nussbaum MA: [2013] Performance evaluation of a wearable inertial motion capture system for capturing physical exposures during manual material handling tasks. *Ergonomics* 56:314-326.
6. Kim S, Nussbaum MA: [2014] An evaluation of methods to classify manual material handling tasks from data obtained using wearable technologies. *Ergonomics* 57:1040-1051.
7. Kim S, Nussbaum MA: [2014] Evaluation of two approaches for aligning data obtained from a motion capture system and an in-shoe pressure measurement system. *Sensors* 14:16994-17007.

Conference Proceedings

1. Nussbaum MA, Shewchuk JP: [2011] Development of a system to enhance residential construction ergonomics and productivity using wall panels. *Proceedings of the International Council for Research and Innovation in Building and Construction (CIB) Meeting: W099 – Safety and Health in Construction*. Washington, DC. August 24 – 26. (Paper #12, 10 pp.).
2. Nussbaum MA, Shewchuk J, Agnew M, Kim S, Jia B, Sarkar S, Haynes C: [2011] Ergonomic panelized construction: analysis and design of material logistics. Poster presented at the Center for Excellence in Logistics and Distribution (CELDi) Spring Meeting. Denver, CO. April 12 – 13.
3. Nussbaum MA, Shewchuk J, Agnew M, Kim S, Jia B, Sarkar S, Haynes C, Gopinath S: [2012] Ergonomic Panelized Construction: Analysis and Design of Material Logistics. Poster presented at the Center for Excellence in Logistics and Distribution (CELDi) Spring Meeting. Atlanta, GA. February 7 – 8

4. Kim S, Nussbaum MA: [2012] Performance of an inertial motion capture system in estimating kinetics. Presented at the Industrial & Systems Engineering Research Conference (ISERC). Orlando, FL. May 19-23. Abstract only.
5. Kim S, Nussbaum MA: [2014] Predicting ergonomic exposures: case study on panelized wall handling. Presented at the Industrial and Systems Engineering Research Conference. Montréal, Canada. May 31-June 3. Abstract only.
6. Kim S, Nussbaum MA: [2014] Inertial motion capture system accuracy in estimating balance-related metrics. Presented at the Industrial and Systems Engineering Research Conference. Montréal, Canada. May 31-June 3. Abstract only.

Publications Submitted or In Preparation

1. Shewchuk JP, Nussbaum MA, Kim S, Sarkar S: Simulation modeling and ergonomic assessment of complex, multi-workers physical processes. Submitted to the IEEE Transactions on Human Machine Systems.
2. Shewchuk JP, Nussbaum MA, Gopinath S: A lean approach and methodology for panelized residential construction. Submitted to the Journal of Construction Engineering and Management.
3. Bastani K, Kim S, Kong Z, Nussbaum MA, Huang W, Zhou Y: Online classification and sensor selection optimization with applications to human manual material handling tasks using wearable sensing technologies. Submitted to the IEEE Transactions on Human Machine Systems.
4. Kim S, Nussbaum MA: Interpolating/extrapolating ergonomics exposures from discrete samples: a case study on panelized wall handling. In preparation.
5. Nussbaum MA, Kim S, and Shewchuk JP: Effects of panel size and stack size on ergonomic risk in panelized residential construction. In preparation.
6. Shewchuk JP, Gopinath S: A decision support tool for panelized residential construction, In preparation.
7. Shewchuk JP, Nussbaum MA, Gopinath S: Planning and design of the panelized residential construction process, In preparation.

INCLUSION OF GENDER AND MINORITY STUDY SUBJECTS

Study Title: A Decision Support System (DSS) for Ergonomic Construction Design

Total Enrollment: 104

Grant Number: U60-OH009761

PART A. TOTAL ENROLLMENT REPORT: Number of Subjects Enrolled to Date (Cumulative) by Ethnicity and Race				
Ethnic Category	Sex/Gender			
	Females	Males	Unknown or Not Reported	Total
Hispanic or Latino	0	19	0	19
Not Hispanic or Latino	7	74	0	81
Unknown (individuals not reporting ethnicity)	0	1	3	4
Ethnic Category: Total of All Subjects*	7	94	3	104
Racial Categories				
American Indian/Alaska Native	0	0	0	0
Asian	1	19	0	20
Native Hawaiian or Other Pacific Islander	0	0	0	0
Black or African American	0	2	0	2
White	6	53	0	59
More Than One Race	0	0	0	0
Unknown or Not Reported	0	20	3	13
Racial Categories: Total of All Subjects*	7	94	3	104
PART B. HISPANIC ENROLLMENT REPORT: Number of Hispanics or Latinos Enrolled to Date (Cumulative)				
Racial Categories	Females	Males	Unknown or Not Reported	Total
American Indian or Alaska Native	0	0	0	0
Asian	0	0	0	0
Native Hawaiian or Other Pacific Islander	0	0	0	0
Black or African American	0	0	0	0
White	0	0	0	0
More Than One Race	0	0	0	0
Unknown or Not Reported	0	19	0	19
Racial Categories: Total of Hispanics or Latinos**	0	19	0	19

INCLUSION OF CHILDREN

The studies conducted under this grant involved children (i.e., those 18-21 years of age). Many workers are children by this standard, and are exposed to conditions of interest here. Specifically where there is a risk of falls and where muscular fatigue may influence this risk. Hence, the results of the research described here have relevance for conditions affecting children.

MATERIALS AVAILABLE FOR OTHER INVESTIGATORS

All experimental data are available. Software (MatLab code) is available for the biomechanical models. These may be accessed by contacting the PI, whose information is provided below. Note that the investigators wish to limit such access to individuals requesting data or software for research purposes only.

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Project ID 655 - Twenty-year trends in work-related injury and illness among union carpenters

Final Progress Report to National Institute for Occupational Safety and Health

Project Title: Twenty-year trends in work-related injury and illness among union carpenters

Dates: September 1, 2010-August 31, 2014 (no cost extension through January 31, 2015)

Grant number: U60 OH009761 **Report No:** 655

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Date: March 6, 2015

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Abbreviations

ANSI	American National Standards Institute
BLS	Bureau of Labor Statistics
CTWW	Carpenters Trusts of Western Washington
EPOC	Effective Practice and Organization of Care
FFH	Fall from height
FTE	Full Time Equivalent
ICD-9	International Classification of Diseases (Version 9)
L&I	Labor and Industries
MSDI	Musculoskeletal disorder or injury
NAICS	North American Industry Classification System
NEISS-Work	National Electronic Injury Surveillance System – Work
NIOSH	National Institute for Occupational Safety and Health
OIICS	Occupational Injury and Illness Coding System
OSHA	Occupational Safety and Health Administration
PLD	Paid lost days
PLT	Paid lost time
RR	Rate ratio
RTW	Return to work
SHARP	Safety and Health Assessment and Research Program
SOII	Survey of Occupational Illness and Injury
UE	Upper extremity
U.S.	United States
WC	Workers' compensation

Project Title: Twenty-year trends in work-related injury and illness among union carpenters
Principal Investigator: Hester J. Lipscomb, Ph.D.
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ABSTRACT

We conducted analyses focused on understanding occupational health and safety experiences of a large cohort of union carpenters in Washington State (1989-2008). Analyses evaluated trends in reported workers' compensation (WC) claims compared to patterns from Bureau of Labor Statistics (BLS) reports. We examined care-shifting for treatment of musculoskeletal injuries and disorders (MSDs). Analyses evaluated falls from height (FFH) with attention to patterns surrounding the 1991 state fall arrest standard.

The construction of this well-defined cohort, work hours, and reported WC experiences linked on an individual basis, identified injury rates that have been, historically, higher than those reported through BLS. Marked declines in WC claim rates over the 20-year period were observed among the cohort. More substantive declines were seen for paid lost time (PLT) injuries than for injuries overall. Struck by injuries and FFH declined more than overexertion injuries. While absolute differences in the cohort rates and those reported through BLS diminished, the relative measures have remained fairly constant.

Rates of FFH decreased 82% in 20 years. There was no demonstrable change since 1996 when adjusting for temporal trend. There was no consistent decline in mean lost days per fall indicating that falls remain serious. Patterns are consistent with decreased injuries in years surrounding the standard when fall rates declined more than other injuries; declines in more recent years are not as substantial as other injuries.

Drywall installers are at high risk for a variety of injuries in this cohort. Despite this, they too experienced marked declines in injury rates. Field experts highlighted changes they believed improved safety and, in some cases, production. Drywall materials were a substantive cause of injury in nearly 20% of the WC claims of these carpenters; a third resulted in paid lost time from work. Drywall carpenters had back injury rates 1.63 (95% CI: 1.48-1.78) times higher than other carpenters.

Work-related reports of musculoskeletal disorders and injuries involving the upper extremity (UE) and the knee were common. UE rates were three times higher than those involving the knee. As WC rates declined, private health care utilization increased. The increase was muted somewhat but still sustained when adjusting for other patterns of health care utilization. Findings suggest considerable shifting of care to private insurance over time.

Survey data with active carpenters document feelings that it is often best not to report less severe injuries to your employer and pressures to utilize private insurance coverage for work-related events. Carpenters reporting poor safety justice on jobsites were particularly likely to fear reporting injuries and were more likely not to report.

This work demonstrates the importance of robust longitudinal data and a cohort approach to analyses. The methods serve as a model for improved occupational safety surveillance. It is clear that use of data from multiple sources is preferable to solely relying on statistics from government surveillance. Considerable insight is gained from workers regarding health and safety experiences, reporting practices, factors influencing decisions about reporting and whether and where they seek medical care.

SECTION 1. SUMMARY: SIGNIFICANT FINDINGS, TRANSLATION, OUTCOMES

We conducted a series of analyses focused on understanding the occupational health and safety experiences of a large cohort of union carpenters in the State of Washington during the twenty-year period, 1989-2008. The analyses included evaluating trends in reported work-related workers' compensation (WC) claims and making comparisons to patterns seen for construction workers in reports from the Bureau of Labor Statistics (BLS), as well as examination of potential care-shifting for treatment of musculoskeletal injuries and disorders (MSDs) through the comparison of WC injury rates and private health care utilization. We conducted detailed analyses evaluating patterns of falls from height and their associated costs with attention to patterns surrounding the fall arrest standard promulgated in Washington State in 1991. Specific analyses focused on the health and safety experiences of carpenters involved in drywall installation who are at high risk of MSDs and falls from height.

Significant Findings

Through the establishment and maintenance of a well-defined occupational cohort of union carpenters, their work hours, and their reported WC experiences that could be linked on an individual basis, we were able to identify injury rates that have been, historically, considerably higher than those reported through the BLS. Marked declines in reported WC claim rates over the 20-year period were observed among members of the cohort, but they were not the same for all groups of workers or all injuries. Greater declines were seen among carpenters with less union tenure and for claims resulting in paid lost time. More substantive declines were seen for paid lost time (PLT) injuries than for injuries overall. Struck by injuries and falls from height (FFH) declined much more markedly than overexertion type injuries. BLS rates also declined but not as markedly; while absolute differences in the carpenter cohort rates and those reported through BLS declined, the relative measures have remained fairly constant.

The rates of FFH, a leading cause of morbidity and mortality in the construction industry, decreased 82% over the 20-year period. Reductions were more modest, and without demonstrable change, since 1996 when adjusting for temporal trend. Younger workers had higher rates of reported falls from height while older workers lost more days following falls. Rates of days lost decreased over time, but there was not a consistent decline in mean lost days per fall. This would indicate that falls that occur remain as serious as they have been. Cost analyses support this as well. The patterns are consistent with decreased FFH surrounding the fall standard during which time the rate of falls declined more than other types of injuries. Crude fall rates have continued to decline, but the decline in more recent years is not as substantial as that seen for other types of injuries. Explanations could include more global efforts designed to control risk as well as changes in reporting practices over time.

Drywall installation is very fast-paced, strenuous work. It is not surprising that these workers are a high risk group, for a variety of injuries including FFH, among members of this cohort. Despite this, they too experienced marked declines in injury rates between 1989 and 2008. Field experts highlighted changes that they believed improved work place safety and, in some cases, production. Drywall materials were a substantive cause of injury in nearly 20% of the WC claims of these carpenters with a third of those resulting in paid lost time from work. Drywall carpenters had back injury rates 1.63 (95% CI: 1.48-1.78) times higher than other carpenters. Rates declined over time but were accompanied by a corresponding increase in private health care utilization. Private utilization also increased with increasing years in the union and with increasing numbers of work-related overexertion back injuries.

Work-related reports of musculoskeletal disorders and injuries involving the upper extremity (UE) and the knee were common among members of the cohort as well, and they accounted for a disproportionate share of paid lost time claims. Claims involving the UE occurred at rates three times higher than those involving the knee. Drywall installers were a particularly high risk group of extremity claims, as they were for back injuries. Declining injury rates were most pronounced for MSDIs of the knee with PLT. As WC rates declined, private health care utilization increased. The increase was muted somewhat but still sustained when adjusting for other patterns of health care utilization. These findings, and the ones related to back injuries among drywall installers, suggest the decline in WC claim rates for MSDIs do not solely represent improved occupational safety in this population of construction workers, but rather also a considerable shifting of care to their private insurance over time. This may have been exacerbated by the economic recession and the accompanying collapse of the building industry. In any event, it appears likely that the declining injury rates observed in WC records do not reflect the full picture of injury experiences of these carpenters.

Survey data with over 1000 active union carpenters document feelings that it is often best not to report less severe injuries to your employer and pressures to utilize their private insurance coverage for work-related events. Further, carpenters who reported poor safety justice on their jobsites (measured through a validated scale) were particularly likely to fear reporting work injuries and were more likely not to report.

Translation of Findings

The findings from this project have led to development of a NIOSH RO1 grant application focused on very high risk drywall installers and practical implications of prevention recommendations [Schoenfisch and Nussbaum; in review 2015].

The focus of this entire project was trying to understand and improve occupational safety and health surveillance. We believe the methods we have developed to assess the potential for care-shifting are important. This is an area that is quite difficult to study in a definitive manner over any significant period of time.

Outcomes and Impact

The project has resulted in 10 peer-reviewed manuscripts, three international presentations, and one U.S. presentation. A master's project for a Duke medical student getting a joint MD/MPH and a doctoral dissertation in epidemiology resulted from the effort. While no clear direct impact can be identified, this is not surprising or unexpected, given the nature of the surveillance work. We do believe that our methods and findings add considerably to the literature that has been developing concurrently on challenges to surveillance and potential remedies. Our ability to construct and maintain this unique occupational cohort has allowed robust analyses of a number of different issues that would not have otherwise been possible. Our ability to adjust for temporal trend through the use of internal control conditions was quite important in these analyses. Many occupational safety questions cannot feasibly be addressed through experimental designs; this body of work demonstrates clearly the importance of robust longitudinal data and a cohort approach to analyses. The methods should serve as a model for improved occupational safety surveillance. It is abundantly clear that the use of data from multiple sources is preferable to solely relying on statistics from government surveillance – or from any other single source. Further, considerable information and insight can be gained from going directly to workers to inquire about their health and safety experiences, reporting practices, and the factors that influence their decisions about reporting or not and whether and where they seek medical care. Even periodic active surveillance activities, such as the survey reported here, can add important detail that allows a better understanding of the highly dynamic nature of work-related injury and illness experiences.

SECTION 2. SCIENTIFIC REPORT

BACKGROUND

Data sources on non-fatal work-related injuries and illnesses and their limitations

Bureau of Labor Statistics (BLS) data and workers' compensation (WC) records are the primary sources of information on occupational injuries and illnesses in the United States. BLS data on non-fatal injuries and illnesses, particularly, are based on reports from Occupational Safety and Health Administration (OSHA) logs from a probability sample of employers. The most recent report from the BLS Annual Survey at the time of our grant application described declining rates of nonfatal workplace injuries and illnesses in private industry for the six consecutive years (BLS; October 23, 2008). Then Secretary of Labor Elaine Chao touted the decline as evidence of "the effectiveness of the strategy of targeted enforcement coupled with prevention through compliance assistance to promote a culture of safety at the workplace" (Professional Safety, 2009). However, there is evidence that this, in fact, may not entirely be the case.

There is growing documentation from a number of reports that indicate that BLS data from the Annual Survey significantly under-estimate risk to workers in the U.S. (Rosenman et al., 2006; Leigh et al., 2004; Azaroff et al., 2002). Through analyses of a series of models Leigh and colleagues estimated that the Annual Survey missed between 33% and 69% of nonfatal injuries in 1999. They went on to say that in light of a lack of substantive change since 1999, the undercounting is expected to have persisted (Leigh et al., 2004). Other data raise questions about whether the reported BLS declines truly represent improvement in work safety as well. In Illinois, BLS reported declining workplace injuries between 1998 and 2003, while the Illinois Trauma Registry data, which does not rely on employer reporting, demonstrated no such comparable decline (Friedman and Forst, 2007a). Analyses of hospital emergency department visits between 1996 and 2004 similarly found no decline in occupational injuries treated in emergency departments in the U.S. (Derk et al, 2004).

Some of the under-recognition of workplace injuries has been described as willful neglect on the part of employers (Pollack and Keimig, 1987; Brown and Barab, 2007) but a variety of other problems have been described as well. Azaroff et al. (2004) provide compelling evidence for their argument that "part of the reported decrease in injury rates grew naturally from a series of profound economic, legal, and political changes that hindered documentation of work-related illnesses and injuries in U.S. data sources." Declines in occupational injuries and illnesses have been partially attributed to changes in recordkeeping regulations over time, most specifically in 1995 and again in 2001 (Friedman and Forst, 2007b).

The issue of potential undercounting of work-related injuries and illnesses has been the subject of recent congressional hearings. In June of 2008, a Majority Staff Report was issued by the Committee on Education and Labor of the U.S. House of Representatives, chaired by George Miller (D-CA), entitled *Hidden Tragedy: Underreporting of Workplace Injuries and Illnesses*. Reliance on self-reporting by employers was described as a major cause of under-reporting. Some under-reporting was attributed to confusion regarding reporting criteria and a lack of appropriate training of OSHA staff to provide appropriate advice to employers. However, the

report pointed to the strong incentives for underreporting by employers including decreased likelihood of being inspected by OSHA and improved chances at securing government contracts.

Workers' Compensation (WC) data provide an alternative source of information on reported work-related injuries and conditions. However, WC reporting requirements vary by state making comparisons more challenging. A bigger limitation of compensation data are that WC reports alone provide no information on the population at risk, limiting analyses to descriptive analyses or proportionate comparisons. An early report documenting the gross inaccuracy of BLS data for construction came from cohort analyses of WC records for union carpenters using individual person-hours of work as the denominator. Findings revealed rates of medical cost or lost-time injuries much higher than BLS estimates (Lipscomb, 1996). The analyses had been made possible through collaboration with the union and the Washington State Department of Labor and Industries allowing the capture of both the population at risk and their reported work-related injuries. This was followed by the work of Glazner et al. (1998) using similar methods, documenting similarly high injury rates in the building of Denver International Airport. Since those reports, numerous investigators have raised concerns about existing data sources and influences of recording practices in the U.S. Using workers' compensation data and physician reporting data from Connecticut between 1995 and 2001, Morse et al. (2005) reported actual numbers of work-related musculoskeletal disorders that were six times higher than those represented in the BLS Annual Survey. While events resulting from acute injury are sometimes reported as more likely to be recognized through the compensation system than chronic diseases or ailments that arise gradually, there is growing evidence that workers often do not file compensation claims for both acute injuries and chronic conditions for a variety of reasons (Biddle et al., 19998; Rosenman et al., 2000; Shannon and Lowe, 2002; Fan et al., 2006) including past experiences, care-giver perceptions, and convenience. The increasing immigrant workforce in construction, which includes workers who may feel vulnerable reporting work-related injuries (Quandt et al., 2006), may also play a role, but it is important to keep in mind that vulnerability related to concerns over job security extend beyond the immigrant workforce.

Delivery of health care to working populations in the U.S.

In the United States, health care delivery for working individuals is theoretically covered by two different insurance systems – private insurance, most often provided through an employer or union, and workers' compensation (WC). Although in theory the systems are separate, and in combination they should provide comprehensive coverage, there are potential overlaps and gaps between them that may hinder our understanding of the health of working populations who are eligible for care through both systems. If a worker is injured on the job or has a work-related condition, he or she must submit a claim through their employer or WC carrier. If the claim is approved, medical care should be paid for by the compensation carrier until it is determined that the person requires no additional care or they have reached a point of maximum medical improvement. While events that are the result of acute injury may be more likely to be recognized through the compensation system than chronic diseases or ailments that arise gradually, there is growing evidence that workers often do not file compensation claims for both acute injuries and chronic conditions for a variety of reasons including past experiences, job security issues, care-giver perceptions, and convenience. Even well-intended safety incentive

programs which provide rewards for periods without recordable injuries can pressure workers not to report (U.S. House of Representatives Majority Report, 2008).

Concerns are also voiced regarding spill-over of non-work-related care into the compensation system. In addition to medical care, workers' compensation provides partial salary reimbursement when loss of time from work is required and payment for permanent impairment that may result from the work-related injury or illness. These benefits are sometimes viewed as incentives for workers to seek care through WC. In addition, there is conflicting literature on the potential significance of cost-shifting practices on the part of providers and insurers (Ducatman, 1986; Zwerling et al., 1991; Butler et al., 1997) related to the diagnosis of conditions as occupationally related and, consequently, to the per capita costs associated with conditions labeled work-related.

In some cases the demarcation between work-related and non work-related injuries or disorders is not always clear -- and can result in contentious situations. Some conditions, including musculoskeletal injuries/disorders, can result in continued problems for the injured worker (Welch et al., 1999) that may extend beyond the coverage for a worker's compensation claim. Compensation carriers have concerns that they may be inappropriately held responsible for care in such cases where workers do not have private insurance coverage. Conversely, to avoid paying for claims that should be the responsibility of a compensation carrier, private insurance companies routinely ask patients if the care for which they are being billed is related to a work-related injury or illness. Coverage for medical care for a disputed condition may also be excluded from payment by a private carrier, leaving the patient uninsured for some services (Ramsey and Rosenstock, 1994). Additionally, employers have been reported to force workers back to work too quickly after work-related injuries and providing inadequate medical treatment (US House of Representatives, 2008).

Significant declines in work-related musculoskeletal back injury rates due to overexertion type activities were identified among a large cohort of union carpenters in Washington State between 1989 and 2003 (Lipscomb et al., 2008a). Members of construction trade unions have health insurance coverage, in most cases, through participation in jointly trustee health and welfare funds. Conversely, outpatient utilization rates for back disorders of a musculoskeletal nature over the same 15-year period among this large cohort of union construction workers who have insurance increased steadily in concert with the decline in work-related claims (Lipscomb et al., 2009). This finding certainly raises the question as to whether the musculoskeletal health of this population is actually improving or not, and different conclusions would be reached depending on what data were available for analyses.

Construction challenges

In the construction trades under-recognition of the magnitude of work-related risk is likely compounded by several factors. The BLS annual survey excludes very small employers -- groups that have been reported to have higher injury rates in construction. In addition, as construction employers report full-time equivalents they may report the count of employees hired, yet many construction workers do not work 2000 hours per year. The result of these two conditions is an under-reported numerator and an over-estimated denominator resulting in an

under-estimation of risk. Inconsistencies in injury rates also suggest that under-reporting, changes in treatment of injuries, or misclassification of employees, may also be responsible (Welch, et al., 2007) for under-counting of the injury experiences in construction. For example, Welch et al., (2007) reported that 14% of construction employers in Massachusetts misclassified workers as independent contractors making injuries to these workers non-recordable on OSHA logs. A recent report from the Center for Construction Research and Training (Dong, 2009) describes the potential under-counting of or misclassification of construction deaths in the Census of Fatal Occupational Injuries; approximately 10% of deaths on construction sites in recent years were to workers not classified in one of the construction trades. Possible explanations include not just coding error, but a failure to classify contingent workers appropriately.

Despite under-recognition of the magnitude of risk, the major causes of workplace morbidity across the industry as a whole are fairly well established. Falls from height are responsible for the greatest mortality and they are also a leading cause of morbidity (US Dept of Labor, 2008; CPWR Chartbook, 2007; Lipscomb et al., 2003a; Courtney et al., 2002; Shah et al., 2003); this is despite considerable knowledge of factors to control risk in the trade. Musculoskeletal injuries and disorders do not contribute to mortality, but they are a leading cause of morbidity in the construction industry including days lost from work. Work-related musculoskeletal conditions are challenging to accurately track for number of reasons (CPWR Chartbook, 2007) including conditions for which the demarcation between work-related and otherwise are not always clear and this can result in contentious situations. Symptoms can wax and wane – many problems tend to be chronic in nature and can create problems for workers for long periods of time (Welch, 1999).

Injuries in which the worker is struck by something are a common source of injury overall in construction. However, these injuries vary tremendously depending on the actual work being done in terms of cause and consequence. Struck by events raise concern about being hit by objects dropped from above or by motor vehicles on large worksites or in roadway construction. However, in drywall work the most common source of struck by injuries is from sharp tools resulting in cuts. In residential carpentry pneumatic nail guns are the most common cause of struck by injuries resulting in carpenters being hit by a nail inadvertently discharged from the gun (Lipscomb et al., 2000). It is easy to see that these injuries, all classified as 'struck by', would require very different prevention activities.

Some groups of construction workers, including residential carpenters, can be particularly difficult to study and BLS data have not historically segregated information on their injury experiences. The fact that they typically work on small and often dispersed sites with only four or five other workers at a given location makes studying them, as well as intervening on their behalf, challenging. Yet, interventions designed to address common problems of other construction workers may not be at all applicable to specialized groups such as these. Because they are a small overall proportion of the construction workforce, exposures and hazards particular to their work get lost in surveillance data for the industry.

Rationale for work

In the absence of good surveillance data, the nature and magnitude of occupational health and safety concerns of high risk populations such as construction workers remain elusive and efforts to evaluate population effects of interventions and preventive activities are sorely hampered. Robust surveillance systems are needed to monitor occupational injuries and disorders over time. However, there are serious, and now well-documented, limitations to existing primary sources of surveillance data for construction workers, including BLS data. Additionally, the blurring of work-related and non-work-related health conditions and medical care further complicates our true understanding of the health of working populations. This work was designed to update important surveillance data for a unique occupational cohort of construction workers, to provide improved information on long-term trends in reported work-related injuries and conditions while exploring potential for shifting of work-related care to their union-provided insurance. These activities allow a more comprehensive assessment of the long-term health and safety of this population than is typically available. Further, targeted analyses allowed exploration of longterm specific prevention efforts/interventions and care patterns.

SPECIFIC AIMS

The lack of accurate occupational injury and illness surveillance data among construction workers is a serious problem. This has resulted in under-recognition of the magnitude and nature of occupational risks while also making the tracking of trends and long-term intervention evaluation very challenging. We proposed to overcome some of these limitations through a large retrospective cohort study of union carpenters in Washington State. The project was designed to support continued work-related injury surveillance among an important occupational cohort that is far superior to Bureau of Labor Statistics (BLS) data for construction workers. We utilized existing administrative data as well as newly collected survey data from construction carpenters. Specific analyses focused on improving our understanding of efforts/interventions designed to reduce a variety of work injuries, associated lost time and costs among construction workers over the last two decades. In each analytical piece considerable emphasis is placed on analyses of trends between 1989 and 2008.

The five original specific aims of the project included:

- 1) Update the Washington State carpenter data to allow definition of a 20-year historical cohort of carpenters who worked in the state between 1989 and 2008, including hours worked, workers' compensation claims and associated medical care, private health insurance claims covered through their union affiliation, and the months of eligibility for this private insurance coverage.
- 2) Establish long-term trends of reported work-related injuries and disorders among this large cohort of union carpenters over a 20-year period.
- 3) Compare annual absolute and relative measures of risk to BLS reports for the construction trades, and evaluate consistency of these measurement differences over time by type and mechanism of injury (acute traumatic injuries vs musculoskeletal injuries; falls, struck by, overexertion) and lost work time.
- 4) Explore possible care and cost-shifting related to treatment of musculoskeletal disorders through joint analyses of workers' compensation claims and claims for medical treatment

covered through the carpenters' union provided health insurance. Separate analyses are planned for musculoskeletal injuries and conditions of the back, upper extremity and knee.

- 5) Conduct injury- and workgroup- specific analyses to:
- Evaluate changes in rates and patterns of falls from height in time windows following the 1991 Washington State Vertical Fall Arrest Standard while adjusting for changes in rates of non-fall related injuries.
 - Evaluate changes in rates of reported injuries from pneumatic nail guns among residential carpenters before and after the 2003 voluntary American National Standards Institute (ANSI) standard calling for shipment of framing nailers to sales outlets with sequential triggers;
 - Evaluate injury risks among drywall installers.

Due to lack of data specific enough to accurately capture and clearly define circumstances surrounding nail gun injuries, this aim was not accomplished. All other aims were accomplished as planned.

RESEARCH DESIGN AND METHODOLOGY

Data Sources

Data for these analyses came from four different sources. The Carpenters Trusts of Western Washington (CTWW) enumerated the cohort of workers and provided their dates of birth, gender, union initiation date, and the union local with which each carpenter was affiliated. The CTWW also provided hours worked each month for each carpenter and a marker of whether they had health insurance coverage each month. The trust is a jointly trustee labor-management fund that provides health and retirement benefits to these workers. Contractors who hire union labor pay a designated amount per hour of work that supports the trust. These funds developed through collective bargaining processes over time in different geographic areas, industries, and trades to provide health insurance coverage for non-work-related medical care. Such arrangements allow union construction workers who have multiple employers over the course of their work life to maintain health insurance coverage for themselves and their families. After meeting eligibility requirements based on work hours, the carpenters receive health insurance coverage at no additional cost. They are allowed to bank hours to allow for continued coverage during periods when they may be between jobs. CTWW also provided us with the line items for health care delivery through the private insurance system for the cohort over the 20-year period between 1989 and 2008.

The Washington State Department of Labor and Industries (L&I) provided records of reported work-related injuries or illnesses for members of the cohort as well as the actual line items for medical care the workers' received through workers' compensation (WC). Because Washington is one of few state administered compensation programs access to the WC records were available from one source. The WC data contained date of injury, coded descriptions of body part injured, nature of injury sustained, type of injury, and paid lost days (which occurs on the 4th day after injury in Washington). Injury codes were assigned based on American National Standards Institute (ANSI) codes until mid-2005 when coding was changed to the Occupational Injury and Illness Classification System (OIICS), developed by the Bureau of Labor Statistics. Based on injury type codes in either system, events were separated into those resulting from a fall from height and all others.

Union carpenters perform a wide variety of construction tasks. The only surrogate for work exposure we had was based on characterization of the primary work of the union local with which each carpenter was affiliated. Characterization of predominant work was based on interviews with business agents for each local that have been conducted each time we have updated information on this cohort since it was initially assembled in 1992. The categories included light commercial (3 stories or less), heavy commercial (including bridge and roadway construction as well as higher rise building), residential construction, drywall installation, millwrighting, and pile driving, as well as a group of carpenters whose primary local assignment was outside Washington.

Lastly, a mailed survey was used to collect information from carpenters who had worked in Washington in 2012. The survey focused on reporting of work-related injuries, exposure to behavioral based safety program elements, and measures of safety climate using the Nordic Occupational Safety Climate (NOSACQ-50) questionnaire [Kines et al., 2011].

Data linkage and analytical approach

Using a unique identifier created by the CTWW we were able to link all of these records on an individual basis without access to personal identifiers such as name or social security number. This linkage allowed us to create very complete longitudinal data on a large cohort of carpenters over a 20-year period. The cohort was dynamic with entrances and exits over time. In analyses age, time in the union, and predominant work were all allowed to vary appropriately over time. The survey data were not linked to the administrative records used in all other analyses.

The analyses focused on work-related events utilized hours worked as a measure of time at risk. Time at risk analyses involving health care utilization was based on months in which each carpenter was eligible for insurance coverage through the trust. Only injuries that occurred in months of union work were included in the analyses in order to define injuries and hours of work on the same basis for rate calculations. Similarly, only health insurance claims that occurred in months the carpenter had health insurance eligibility were included in those analyses.

A cohort approach was used in the analyses of linked administrative records. The precise modeling approaches varied depending on the question being explored and the nature of the data being used to do this. To assess higher risk groups within the cohort, Poisson regression was used to calculate adjusted rate ratios using the natural log (ln) of hours worked as the offset variable [Nizim, 2000]. Analyses of health care utilization and costs utilized models more appropriate for multiple measures for the same individuals over time and highly skewed data including negative binomial regression [Byers, 2003] and models incorporating generalized estimated equations as appropriate [Zeger, Liang and Albert, 1988]. The natural log (ln) of months of eligibility for insurance coverage was used instead of hours worked in order to define events and denominator data on the same basis for rate calculations. In several of these analyses, we took advantage of internal comparisons of different conditions or diagnoses to control for temporal trend. For example, in our falls analyses we assessed rates over time adjusting for patterns of non-fall injuries that would not directly be affected by prevention efforts directly focused on falls. In analyses of private health care utilization for MSDIs of the upper extremity and the knee, we used the utilization patterns for acute respiratory problems, another very common reason to seek health care, to adjust for temporal changes in health care use over the 20-year period. The survey data were analyzed with descriptive statistics and log-binomial regression to provide more accurate estimates of prevalence ratios in the presence of common outcomes than using logistic regression [Skov, 1998].

Manuscripts have been developed that detail specifics of each set of analyses conducted. An annotated list appears at the end of this document. The only exception was the comparison of

the cohort experience to that reported in the BLS data. These analyses have not been published elsewhere and detail follows below.

Comparisons of cohort injury experiences to BLS rates over time

Our earlier reports [Lipscomb, et al. 1996, Lipscomb, et al. 2008] had documented that this cohort of union carpenters in Washington State had higher injury rates than those reported by the Bureau of Labor Statistics (BLS) for the construction industry. Our initial objective in these analyses was to describe trends in reported work-related injuries and illnesses among this cohort and to compare absolute and relative differences in injury rates for the carpenters in the cohort against those reported for the construction industry as a whole through BLS Survey of Occupational Illness and Injury (SOII) over time.

Union carpenters perform a wide variety of construction industry tasks, including drywall installation, residential building, roadway and bridge construction, pile-driving, and light and heavy commercial building, including high-rise construction. Because of the varied nature of work performed by these carpenters, we compared injury rates of the cohort to those of the overall construction industry. We used BLS incidence rates of all recorded injuries and illnesses and all time lost cases (cases in which time off extends beyond the day of injury) for the construction industry for the years 1992-2008 provided by The Center for Construction Research and Training. Rates of injuries involving lost time for the more common construction industry injury mechanism groupings: “struck by an object,” “fall to a lower level,” and “overexertion with lifting” were also provided. BLS work-related injury and illness estimates presented from the SOII are derived from Occupational Safety and Health Administration (OSHA) logs of a probability sample of surveyed employers each year.

To approximate OSHA recordable injuries, we identified cases that resulted in paid medical care or paid lost time (PLT) Since PLT occurs after the third lost day in Washington, the estimates for the cohort are conservative compared to BLS definitions. To facilitate comparison to BLS construction industry data, approximated OSHA-recordable incidence rates were expressed per 200,000 hours worked, equivalent to the BLS metric of 100 full time-equivalents (FTE). For the claims involving PLT, the incidence rates were per 20,000,000 hours worked (10,000 FTEs), the metric commonly used by BLS to report incidence rates for work-related injuries and illnesses involving lost time. Incidence rates and 95% confidence intervals were calculated by year. Absolute and relative differences in injury rates were calculated between the carpenter cohort and construction industry estimates reported through BLS SOII.

KEY FINDINGS

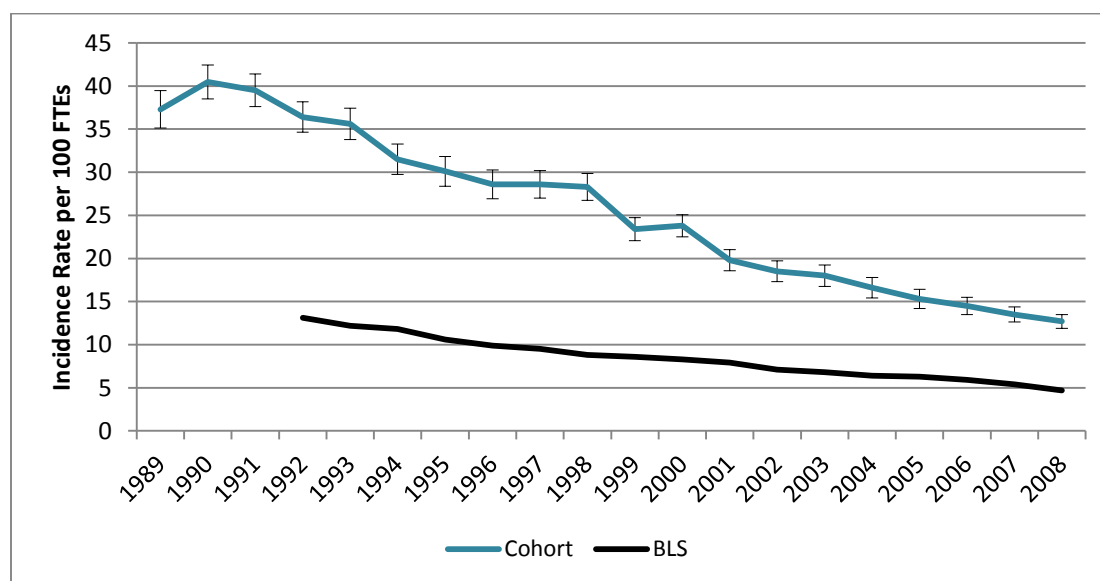
Brief Description of the Cohort and their reported injury experiences

We identified a cohort of 24,830 carpenters who worked a total of 192,371,021 union hours between 1989 and 2008. They were predominantly male (97%). Carpenters entered observation in the cohort at a mean age of 34.2 years (median 32.7 years). The mean age was 38.2 years in 1989 and peaked at 44.9 years in 2005, declining to 42.0 years in 2008. A total of 27,080 WC claims were reported and accepted for coverage over the 20-year period.

Comparisons to BLS Estimates

The carpenter cohort's crude incidence rate of medical or PLT claims (with 95% confidence intervals) were compared to the BLS's point estimates for the construction industry beginning in 1992 (without 95% CIs as standard errors were not available) for all OSHA- recordable cases by year in **Figure 1**. The carpenter cohort's incidence rates were consistently higher than BLS estimates of OSHA- recordable claims for workers in the construction industry; the discrepancy in absolute rate differences decreased through the years. In 1992, the absolute difference between the cohort's approximated OSHA-recordable claims incidence rate and the BLS incidence rate was 24.0 events per 100 FTEs. By 2008, the absolute difference between the incidence rates had declined to 8.0 events per 100 FTEs. However, relative rate differences changed very little over 20 years with the carpenters' injury rates consistently 2 to 3 times higher than those reported through BLS for the construction industry (**Table I**).

Figure 1: Incidence Rates of Workers' Compensation Claims Involving Paid Lost Time or Medical Costs (OSHA-Recordable), Union Carpenters, Washington State (1989-2008) Compared to BLS Incidence Rates of All Cases for the Construction Industry (1992-2008)*



*Paid lost time occurs after the 3rd lost day in Washington State. The BLS considers lost time to occur the day after initial injury.

Table I: Unadjusted Incidence Rates, Absolute and Relative Rate Differences of Claims for Union Carpenters in Washington State Compared to BLS All Injury and Illness Cases for the Construction Industry (1992-2008)

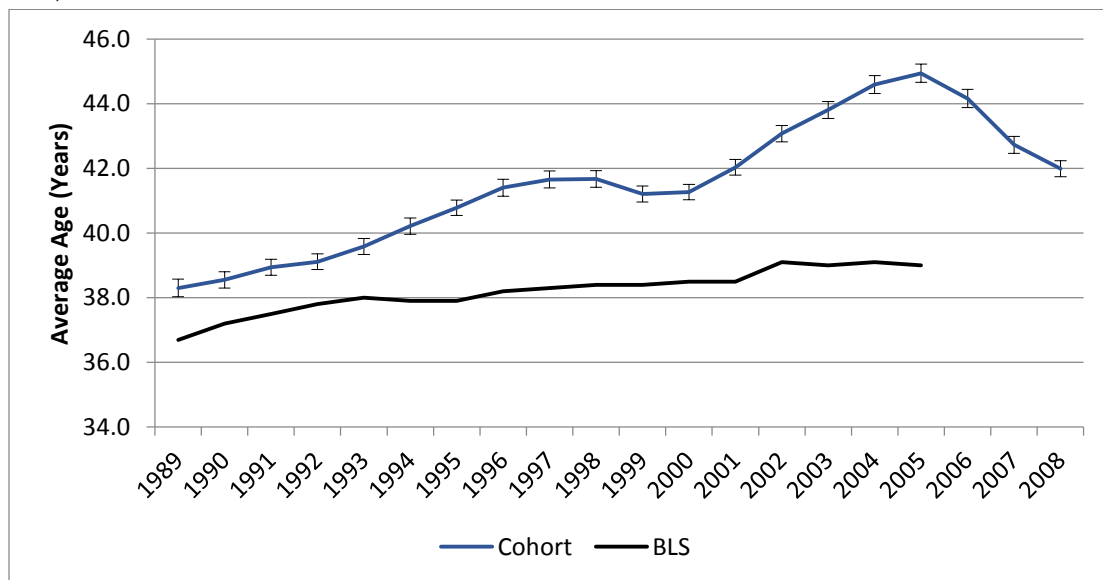
Year	Involving Paid Lost Time or Medical Expenses				Involving Paid Lost Time			
	Cohort Incidence Rate*	BLS Incidence Rate*	Absolute Difference	Relative Difference	Cohort Incidence Rate*	BLS Incidence Rate**	Absolute Difference	Relative Difference
1992	36.4	13.1	23.3	2.8	883.2	529.5	353.7	1.7
1993	35.5	12.2	23.3	2.8	892.8	490.5	402.3	1.8
1994	31.5	11.8	19.7	2.7	740.8	486.2	254.6	1.5
1995	30.1	10.6	19.5	2.8	687.1	417.6	269.8	1.7
1996	28.6	9.9	18.7	2.9	609.9	372.3	237.6	1.6
1997	28.6	9.5	19.1	3.0	644.6	364.8	279.8	1.8
1998	28.3	8.8	19.5	3.2	553.2	326.9	226.3	1.7
1999	23.4	8.6	14.8	2.7	462.2	331.3	130.9	1.4
2000	23.8	8.3	15.5	2.9	444.7	318.9	125.8	1.4
2001	19.8	7.9	11.9	2.5	403.1	304.6	98.5	1.3
2002	18.5	7.1	11.4	2.6	422.7	276.8	145.9	1.5
2003	18.0	6.8	11.2	2.7	309.9	259.4	50.5	1.2
2004	16.6	6.4	10.2	2.6	317.2	243.7	73.5	1.3
2005	15.2	6.3	9.0	2.4	244.5	239.5	5.0	1.0
2006	14.5	5.9	8.6	2.5	229.9	219.5	10.4	1.1
2007	13.5	5.4	8.1	2.5	225.6	190.3	35.3	1.2
2008	12.7	4.7	8.0	2.7	204.5	174.3	30.2	1.2

*Incidence rates are calculated per 200,000 hours worked (100 FTEs).

**Incidence rates are calculated per 20,000,000 hours worked (10,000 FTEs).

The cohort was slightly older than the mean age of workers represented in the BLS construction data (Figure 2).

Figure 2. Mean age of Washington carpenter cohort compared to that of U.S. construction workers reported through BLS, 1989 to 2008.



Twenty year trends [detailed findings in McCoy et al., 2013]

The rate of reported work-related WC claims peaked in 1991 at 44.9 (95%CI: 41.9-48.2) per 200,000 hours of work or 100 fulltime equivalents (FTEs). The lowest rate was observed in 2008 at 15.9 (95% CI: 14.5-17.3) per 100 FTEs. Eighty-six percent (86%; n=23,351) of claims resulted in medical care or paid lost time from work, approximating an OSHA recordable injury. Twenty-two percent (n=5,048) involved paid lost time from work which occurs after the third lost day in the State of Washington. Claims with PLT accounted for 25% of claims in earlier years, decreasing to about 16% between 2005 and 2008. Injury rates were consistently highest for injuries resulting from being struck by or against something, followed by falls from height and then overexertion injuries. Injuries from all three of these causes declined markedly over time, with greater improvements seen for struck by events and falls from height than for overexertion activities. Injury rates have historically been higher among younger carpenters and those with less union tenure; the differences were less pronounced when analyses were limited to injuries that resulted in paid lost time from work. Over twenty years, the differences based on both age and tenure diminished considerably.

Falls from Height and Associated Costs [detailed findings in Lipscomb et al, 2014a and 2014 b]

There were 1,511 reported injuries resulting from FFH between 1989 and 2008 among members of the carpenter cohort. These injuries represented 5.8% of all WC claims with the proportion varying from a high of 8.9% of claims in 1989 to a low of 3.5% in 1996. Nearly 20% (17.5%) of the injuries involved multiple body parts. The rate of injuries from FFH was 1.57 (95%CI: 1.47-1.67) per 200,000 hours worked. There were 570 (37.7%) FFH that resulted in paid lost time from work with a mean of 122 lost days (SD=344; Median=0). Younger workers had lower rates of these more serious falls although they had higher rates of FFH overall as did those in the first 4 years of union tenure. The total number of paid lost days represented 192 (95% CI: 180-204) PLDs per 200,000 hours worked. The rate of PLDs was highest among carpenters over age 40 and among those with 4-6 years of union tenure. Those affiliated with a local doing drywall installation or residential carpentry had the highest rates of FFH while millwrights had the highest rate of paid lost days. Injury rates declined 82% over the 20-year period; when accounting for temporal trend in acute injuries that did not result from FFH, reductions were more modest and without demonstrable improvement since 1996. Crude rate reductions were greater for falls that resulted in PLDs than for those involving medical care alone.

Over twenty years FFH were responsible for \$66.6 million in direct WC payments or \$700 per year for each fulltime equivalent of carpenter work. They accounted for 15% of WC costs. Costs declined but not in a monotonic fashion. Reductions in costs were more pronounced for indemnity than for medical care. Mean costs were over twice as high among carpenters over 50 than those under the age of 30 but their costs rates were only modestly higher. Primary reductions in WC costs reflect a reduction in the frequency of falls, but FFH that occur remain quite serious as measured by dollars spent. Millwrights have few falls but when they occur they are costly; drywall installers have many falls and costly ones.

Work-related Musculoskeletal Disorders and Injuries Involving the Upper Extremity or the Knee [detailed findings in Lipscomb et al., 2015a and 2015b in press]

Musculoskeletal disorders and injuries were common and accounted for a disproportionate share of paid lost work time claims. Upper extremity MSDIs were three times more common among these carpenters than those involving the knee. Patterns of risk varied by the extremity involved as well as by age, gender, time in the union, and type of work. Drywall carpenters accounted for the greatest public health burden among the cohort. Greater gains over time were seen for injuries involving falls or being struck than for those classified as resulting from overexertion.

Drywall [detailed findings in Schoenfisch et al, 2003, 2014a and 2014b]

Individuals involved in drywall installation had injury rates higher than their carpenter peers in other types of predominant work. Rates were particularly high for those in their last 2 years of apprenticeship training. Over 20 years their injury rates overall declined 73.6%. Drywall material was a contributing factor in nearly 20% of injuries (19.7%) and a third of these injuries resulted in PLT compared to 19.4% of injuries from other sources. Rates of injuries from overexertion that involved drywall material declined substantially and this pattern was sustained even after controlling for temporal trend. Experts in the field report improved safety practices over time as well as increased production.

Drywall installers were at particularly high risk for overexertion back injuries. While these rates declined over time, their rates of private health care utilization increased after the mid-1990s, with greater union tenure, and with increasing numbers of work-related events.

Drywall installers' FFH rates declined over time and varied little by worker age and time in the union. However, among FFH involving drywall sheets, workers with <10 union years were at high risk. Narratives consistently described the surface from which workers fell, commonly scaffolds (33%), ladders (21%), and stilts (13%). Work task, height fallen, protective equipment use, work speed, weather, influence of other workers/workgroups, and tool/equipment specifics were not often reported.

Care shifting [details in Lipscomb et al, 2015 in press]

A total of 38,438 health care visits were identified among members of the cohort for upper extremity MSDIs and 21,914 for MSDIs involving the knee. Utilization rates were 29.5 (95% CI: 27.7-31.4) and 16.7 (95% CI: 15.7-17.8) per 100 person-years of private insurance utilization. As WC claims for these disorders declined 250% for the UE and 300% for the knee, private health care utilization increased 300% and 340%, respectively over the 20-year observation period. When adjusting for the pattern of health care utilization for acute respiratory problems, another very common reason to seek medical care, the magnitude of the private utilization increase diminished somewhat (30%) but the contrasting patterns remained. Of note, women had 20% greater private utilization for UE problems than men, and 70% greater utilization for knee problems.

Survey findings [details in Lipscomb et al., in press 2015]

A total of 1155 carpenters who had worked union hours in 2012 responded to our mailed survey request representing a response rate of 20%. Respondents were from 19 to 74 years of age (mean 48 years; median 50 years) and they had been in the union from less than a year to over 50 years (mean 18 years; median 16 years). Almost all of the respondents had worked in

carpentry for over 5 years (94.5%; n=1074), and the vast majority had been injured at work (84.5%; n=958).

In their current workplace most carpenters felt they could report injuries without fear of reprisal (76.2%; n=856) and two-thirds felt jobsite injuries got reported most or all of the time (n=721). Post-injury drug testing was common on the sites where these carpenters worked (77.5%; n=879) while other behavioral-based safety efforts were less common such as rewards for supervisors for low injury rates (15.3%) to 36.7% for policies of discipline for not reporting injuries. Safety climate domains of management safety justice, worker safety priority, and peer safety communication were correlated as expected and had acceptable measures of internal reliability. For each of these measures, poorer safety climate was associated with higher prevalence of failure to report work injuries. The effect of safety justice was most pronounced with carpenters on sites with the poorest safety justice over 3 times more likely (aPR 3.5; 95% CI 2.4-4.9) not to report a work injury and over 6 times more likely (aPR 6.3; 95% CI 3.7-10.5) to fear reprisal for so doing. Over 50% agreed that too many carpenters were afraid they would be terminated for an injury at work and 47% reported that carpenters felt pressures to use their private insurance for work injury care. Few (23%) agreed that “you are looking for another job if you get hurt” and that it was best not to report any injury (13%), however nearly half (49%) felt it was best not to report more minor work injuries. Over half of the participating carpenters (n=611; 52.9%) wrote comments and/or called to provide more detail about their impressions. They described tremendous variability across job sites in approaches to safety and injury reporting. They also described that safety was sometimes for show and that production speed was problematic at times. They had experienced overt and subtle pressures not to report injuries and they provided examples of frank injustices. However, they also said that safety was improving over time.

DISCUSSION

We sought to improve occupational safety surveillance for a large cohort of union carpenters in the State of Washington through the use of individually linked, combine administrative data. By combining data on union carpenters who had worked in the state and their hours worked with workers compensation records we were able to calculate, what we believe, are reasonably accurate rates of reported work-related injuries that can be used to assess patterns over time. The addition of private health insurance claim records for the cohort, and time they were eligible for coverage, provided a fairly unique opportunity to look more broadly at the interplay in care across two different payment systems. In the process we learned a lot.

Absolute differences between the cohort and BLS incidence rates diminished substantially over time with smaller discrepancies for PLT claims particularly in later years of observation. The relative difference of approximated OSHA-recordable claim rates was consistently 2 to 3 times higher among the carpenters compared to BLS rates for the construction industry. In 1993 the point estimate for the rate of PLT claims was 80% higher among the carpenters compared to the BLS construction industry; the rate was 20% higher in 2008. Even without standard errors for the BLS data it is clear that rates for claims involving PLT for the carpenter cohort and BLS construction industry essentially converged in the later years of observation.

There are methodological reasons that these data sources would yield somewhat different results. BLS data on non-fatal injuries and illnesses are based on a probability sample of employers' OSHA logs. National estimates generated from these sampled data are then presented each year in the BLS Annual Survey of Occupational Injury and Illness (SOII). The SOII includes all workers, including administrative staff, who would obviously be at lower risk of serious injury than those working with the tools such as the union carpenters we studied. However, their contribution to the overall injury rate would be expected to be fairly minimal. The SOII does not include workers of federal, state, and local government agencies, household workers, the self-employed, and workers of employers with fewer than 11 employees [US Department of Labor, Occupational Safety & Health Administration 2001]. These exclusions translate to approximately 25% of the construction labor force [Dong, et al. 2011]. If these excluded groups have higher risk of injury, the BLS estimates will then be underestimated.

Some of the observed decline in BLS reports may also be an artifact of policy changes that have resulted in less rigorous reporting standards [Friedman and Forst 2007]. For example, in 2002, changes in OSHA recordkeeping required that a work-related injury or illness that was caused by the aggravation of a pre-existing condition must be a *significant* aggravation, rather than just an aggravation, to be considered OSHA-recordable. A significant aggravation is defined as one that results in death, loss of consciousness, more than one day of lost work time or work restriction, transfer to another job, or medical treatment for a new or change in injury or illness. Additionally, the 2002 changes expanded the definition of work restriction: work restriction must extend beyond the day of injury in order for an injury or illness to be considered OSHA-recordable. These changes could have reduced the number of events that would be recorded on OSHA-logs, the source of BLS data. However, they would not have affected the reporting of workers' compensation claims.

Our comparisons to BLS data involved a large group of unionized carpenters in one state.

Our cohort aged overtime and the average age of our cohort was slightly older than the average age of construction workers nationally; this is consistent with reports that the average age of union construction workers is higher than the average age of non-union construction workers nationally [The Center for Construction Research and Training 2007]. With the average age of construction workers nationally younger than that of this carpenter cohort, we might expect the BLS incidence rates to be higher, not lower than the carpenter cohort's, given that our analysis and previous research [Salminen 2004, Chau, et al. 2004] has demonstrated that younger workers report more work-related injuries. However, in later years we saw little effect of age on injury rates among the cohort members.

Relative differences between the carpenter cohort's and BLS construction industry's rates for OSHA approximated claims remained constant while relative differences for the subset of more serious injuries that resulted in paid lost time present in earlier years of observation diminished in more recent years. It is striking how the WC data and BLS data track over time, since each has its own set of obstacles to truth and each has changed over time. We cannot identify in these surveillance data exactly what the cohort/BLS ratios converging over time for PLT but not for claims approximating an OSHA recordable event actually reflect.

Cost-shifting may have contributed to decreases in reporting to BLS by construction workers nationally as well. In 2005 the proportion of construction workers with access to private health insurance was 84% and 52% nationally for unionized and non-unionized workers, respectively [The Center for Construction Research and Training 2007], the effect of cost-shifting for construction workers nationally may be less pronounced than in this carpenter cohort.

There were marked reductions in the rate of WC claims filed by member of this cohort between 1989 and 2008, and they were more pronounced for injuries resulting from being struck by or against something and falls from height than they were for overexertion injuries. Given the evidence we see for cost-shifting to the CTWW private insurance coverage for MSDIs (back, upper extremity, and knee) the lack of comparable progress in reduction of overexertion injuries is of particular note. This indicates that far less progress has been made in addressing overexertion injuries than one would assume in looking at the WC experience of these construction workers. Care shifting is difficult to assess and our conclusions are certainly inferential. However, we do not know of a better way to look at this issue over a substantial period of time than with the methods we have used.

We had previously reported data that supported evidence of effect of the Washington State Vertical Fall Arrest Standard that was promulgated in 1991 [Lipscomb et al., 2003a]. Crude rates of FFH have continued to decline, but not at the same pace. When controlled for non-fall injury rates, there have not been substantive changes in FFH since the late 1990s. This could reflect greater safety overall reflecting more global efforts to control risk. Rates of PLDs associated with FFH decreased, but there was not a consistent decline in mean lost days per falls. This would seem to indicate that the severity of FFH that occur remains high. Analyses of cost data confirm this notion; WC payments decreased particularly through 1996, but mean costs per FFH remained high. Mean costs for older injured carpenters were significantly higher than those for younger victims, but their cost rates were only modestly higher. The contrasting rate and cost findings for millwrights is particularly interesting. Millwrights have low rates of FFH

but high cost rates; when they fall the injuries are severe. Millwrights work in industry and it could be possible that their falls are more likely to occur to a concrete floor perhaps.

A number of findings from our analyses of the experience of this cohort demonstrate high risk among drywall installers relative to their peers doing other types of carpentry work. Drywall installation is very fast-paced, labor intensive work. Even though union carpenters are not paid by the piece, workers knew the demands required and how much time was allotted for completion of jobs. The fast-pace likely contributes to morbidity among these workers given the common report that speed and safety do not mix well in construction. Drywall sheets have gotten larger over time and this may have some impact on injury rates. Sheets could become unmanageable by one carpenter making it more necessary for crews to work together or in teams. Workers might also continue to handle sheets on their own even when their view is obstructed or the size and weight of the sheet contribute to the danger of falling. The relative lack of progress in control of struck by injuries among these workers is notable and may also relate to size of drywall. This group should clearly be targeted for prevention efforts including efforts to determine if current prevention recommendations made by NIOSH are feasible and being utilized.

The cross-sectional survey data came from 20% of the approached workforce in 2012. Respondents differed from the overall group in several notable respects; they were older than average and they had almost all been in carpentry for over five years. The vast majority of had also experienced a work injury. We recognize the data obtained from them cannot be assumed to be generalizable. However, the high prevalence of injury among these carpenters may simply reflect long-term injury risk in this industry [Dong et al., 2014]. Furthermore, these are the carpenters whose perspectives we wanted. We clearly drew a group who thought the issues we were examining were important with over 50% offering free text, enlightening comments or calling to speak directly about their experiences. The data do not allow us to speak to the relationships between domains of safety climate and injury incidence. However, they do provide evidence that poor safety climate especially low management safety justice inhibits reporting of injuries. If safety climate is associated with rates of injuries, under-reporting may be even more prevalent on sites with higher injury rates.

Limitations and Strengths

These analyses, in large part, were based on existing administrative data that were not originally collected for surveillance purposes or epidemiologic analyses. The WC claims represent claims that were reported and accepted for coverage. We know that the assumption cannot be made that they present an entirely accurate portrayal of the injury experiences of members of this cohort. In fact, some of our analyses confirm that they do not. We had no direct measures of work exposures for these carpenters; our assignment of predominant work of the union local the carpenters affiliated with is only a crude assessment of potential exposure. However, our common sources of surveillance data – BLS SOII, WC, NEISS-Work -- also lack exposure measures.

During the 20-year period of interest a number of things were changing throughout the U.S. including more attention to rapid return to work following injuries. This grew from concern over

rising WC costs and was supported by rehabilitation efforts purporting this to be good for workers as well as businesses. We were not able to identify when workers may have been allowed lighter duty work or for how long that might have been the case; both might have been useful in helping us understand the patterns we observed over time. More accommodation in later years could account for some of the decrease in paid lost time injury rates [Welch and Hunting, 2003].

Recognizing these limitations, there are also some distinct strengths in these analyses. Interestingly, some of the advantages correspond directly to the disadvantages. Because the administrative data were collected for other purposes they are not likely to be influenced by recall bias that might occur in trying to capture information about events that occurred some time ago. They allow the study of a large number of workers, who in this case, would be difficult to follow because of the organization of construction work. The study of a unionized workforce was also advantageous. We would not otherwise have been able to assemble and maintain this large cohort. The fact that they had access to private health insurance coverage through the CTWW also made it possible for us to explore the potential for cost/care-shifting in a quite robust manner that would otherwise have been impossible. We recognize that our results are not generalizable across all carpenters, but they provide important insight and findings that are likely quite generalizable to the large numbers of unionized construction workers in the U.S.

Clearly, the greatest strength of these data lies in our ability to link on an individual basis data that clearly defined this important occupational cohort including their work hours by month over 20 years, their workers compensation records, and their health care claims for care delivered through private insurance coverage. Further, we had a marker of months in which they were eligible for this insurance coverage. Once carpenters meet their minimum hours for coverage there is no fee and coverage is universally applied. Because Washington has a state run WC program, one of few in the U.S., we were able to access all claims filed in the state from one source. The longstanding collaborations in place between our academic team, the CTWW, and the Department of Labor and Industries allowed the initial assembly of a 4-year cohort in the early 1990s that has subsequently been updated on several occasions. These data now define this quite unique, well-established, large occupational cohort of construction workers for whom we have comprehensive data on their use of health care services through two entirely different payment systems for a 20-year period. These data are well-suited to longitudinal cohort-type analyses with robust statistical methods as we have demonstrated. The ability to use internal comparison conditions or injuries to control for temporal trend is analytically strong and very important in exploring questions that are not suited to experimental designs. Such analyses can help provide an evidence base for occupational safety and health interventions, given the associated challenges. In the assessment of quality studies, protection from secular trend is considered important [EPOC, 2008]. Yet we need information about longer-term outcomes, which will always be influenced by other factors.

CONCLUSIONS

The data assimilated here are not widely available for a variety of work groups, but the process of linkage on an individual basis while maintaining confidentiality is a useful model. The robust analyses conducted, that included use of internal comparisons and use of different injuries and conditions within the same population, provide examples of how observational data can be controlled for temporal trend. The importance of this in understanding patterns of work-related injuries over time cannot be emphasized enough. Many occupational safety questions are not amenable to inquiry with experimental designs, making the development of more robust ways to analyze observational data important particularly as we try to understand long-term patterns.

These analyses add to the evidence that the use of more than one source of data can improve occupational safety and health surveillance. Further, they confirm utility in including workers themselves as important resources in understanding their injury experiences and motivations for reporting and using health care resources. We believe the findings provide evidence of improvements in safety over the twenty-year observation period. However, the gains do not appear to be as great as one would assume by only examining workers' compensation records. This conclusion is supported through workers' personal reports.

These findings demonstrate that analyses of costs, as well as incidence, can be particularly useful. We believe that the metric of cost rates are not just meaningful, but also powerful; in this cohort, the cost of FFH was \$0.35 for every hour of carpenter work or \$700 for every fulltime carpenter per year. Further contrasting findings based on incidence rates to those based on cost rates can be enlightening; millwrights had relatively low rates of falls from height, but their costs rates were high meaning when they fall the events are serious. These falls warrant further exploration on a case basis to determine what risk factors might account for this pattern and what ameliorative efforts could be initiated.

Drywall installers clearly stand out as a high risk group in many respects. Their injuries are not limited to musculoskeletal conditions, although those are common. They also experience serious and frequent falls from height. The sheets they work with are often directly implicated as a source of injury. Given the burden of work injury among this group they should be targeted for intervention efforts. Consideration should be given to the very fast-paced nature of this type of work.

Perhaps the most significant findings in these analyses are those supporting evidence of care/cost-shifting from workers' compensation to private insurance coverage. It is quite clear that the two systems of care do not operate independently in the case of musculoskeletal conditions involving the back, the upper extremity, or the knee.

ACKNOWLEDGEMENTS

We acknowledge key contributions made by Larry McNutt the administrator at the Carpenters Trust of Western Washington. Without his cooperation and support the assembly of this unique occupational cohort would not have been possible. We also acknowledge the contributions of Lin Conley at CTWW for her assistance with data transfer and coordination of linkage with the Department of Labor and Industries. Finally, we thank the carpenters who participated in the survey for taking the time to help us learn more about their experiences.

Darrin Adams at the Department of Labor and Industries coordinated data transfer with Lin Conley and he reviewed all manuscripts, making important and substantive suggestions for analyses and presentation.

Program Director/Principal Investigator (Last, First, Middle):		Lipscomb, Hester J.			
Inclusion Enrollment Report					
Study Title:		20-year Trends in Work-related Injuries and Disorders among Carpenter			
Total Enrollment:		25985	Protocol Number:		
Grant Number:		U60OH009761 Project ID: 655			
PART A. TOTAL ENROLLMENT REPORT: Number of Subjects Enrolled to Date (Cumulative) by Ethnicity and Race					
Ethnic Category	Females	Males	Sex/Gender Unknown or Not Reported	Total	
Hispanic or Latino					**
Not Hispanic or Latino					
Unknown (individuals not reporting ethnicity)	646	24,182	1,155	25,985	
Ethnic Category: Total of All Subjects*	646	24,182	1,155	25,985	*
Racial Categories					
American Indian/Alaska Native					
Asian					
Native Hawaiian or Other Pacific Islander					
Black or African American					
White					
More Than One Race					
Unknown or Not Reported	646	24,192	1,155	25,985	
Racial Categories: Total of All Subjects*	646	24,192	1,155	25,985	*
PART B. HISPANIC ENROLLMENT REPORT: Number of Hispanics or Latinos Enrolled to Date (Cumulative)					
Racial Categories	Females	Males	Sex/Gender Unknown or Not Reported	Total	
American Indian or Alaska Native					
Asian					
Native Hawaiian or Other Pacific Islander					
Black or African American					
White					
More Than One Race					
Unknown or Not Reported	646	24,192	1,156	25,985	
Racial Categories: Total of Hispanics or Latinos**	646	24,192	1,155	25985	**
* These totals must agree. ** These totals must agree.					

Annotated publication list

The project resulted in ten peer-reviewed publications. Each is listed below with annotations explaining the specific aim of the project from which the work resulted.

- McCoy AJ, Kucera KL, Schoenfisch AL, Silverstein BA, Lipscomb HJ: [2013] 20 years of work-related injury and illness among union carpenters in Washington State. *American Journal of Industrial Medicine* 56:381-388.
*This report, which was the initial publication from the project, addressed **Specific Aims 2 and 3** which established long-term trends of reported work-related injuries and disorders among this large cohort of union carpenters over a 20-year period, and made comparisons to BLS reports. We evaluated changes over time by type and mechanism of injury (acute traumatic injuries vs musculoskeletal injuries; falls, struck by, overexertion) and lost work time. The publication resulted from the MPH project for Dr. McCoy.*
- Lipscomb HJ, Schoenfisch AL, Cameron W, Kucera KL, Adams D, Silverstein BA: [2015] Workers' compensation claims for musculoskeletal injuries and disorders of the upper extremity and knee among union carpenters in Washington State, 1989 to 2008. *American Journal of Industrial Medicine* 58(4): 428-436.
- Lipscomb HJ, Schoenfisch AL, Cameron W, Kucera KL, Adams D, Silverstein BA: [2015] Contrasting patterns of care for musculoskeletal injuries and disorders of the upper extremity and knee through workers' compensation and private health care insurance among union carpenters in Washington State, 1989 to 2008. *American Journal of Industrial Medicine* (in press as companion pieces)
*These two reports addressed **Specific Aim 4** which explored possible care and cost-shifting related to treatment of musculoskeletal disorders through joint analyses of workers' compensation claims and claims for medical treatment covered through the carpenters' union provided health insurance. Separate analyses were conducted of musculoskeletal injuries and conditions of the back, upper extremity and knee. Back analyses were summarized in a erratum to the *Journal of Occupational and Environmental Medicine* that corrected and updated earlier analyses.*
- Lipscomb HJ, Schoenfisch AL, Kucera KL, Cameron W, Adams D, Silverstein BA: [2014] How well are we controlling falls from height in construction? Experiences of union carpenters in Washington State, 1989-2008. *American Journal of Industrial Medicine* 57(1):69-77.
- Lipscomb HJ, Schoenfisch AL, Cameron W, Kucera KL, Adams D, Silverstein BA: [2014] Twenty years of workers' compensation costs due to falls from height among union carpenters, Washington State. *American Journal of Industrial Medicine* 57(9):984-991.
*These two reports address **Specific Aim 5**. The first part of this aim was designed to evaluate changes in rates and patterns of falls from height in time windows following the 1991 Washington State Vertical Fall Arrest Standard while adjusting for changes in rates of non-fall related injuries. The initial analyses were supplemented with analyses of costs over the period.*

- Schoenfisch AL, Lipscomb HJ, Marshall S, Cameron W, Richardson D, Casteel C, Brookhart A: [2013] Work-related injuries among union drywall carpenters in Washington State, 1989-2008. *American Journal of Industrial Medicine* 56(10):1137-1148.
- Schoenfisch AL, Lipscomb HJ, Marshall S, Casteel C, Richardson D, Brookhart A, Cameron W: [2014] Declining rates of work-related overexertion back injuries among union drywall installers in Washington State, 1989-2008: Improved work safety or shifting of care? *American Journal of Industrial Medicine* 57(2):184-194.
- Schoenfisch AL, Lipscomb HJ, Cameron W, Adams D, Silverstein BA: [2014] Rates of and circumstances surrounding work-related falls from height among union drywall carpenters in Washington State, 1989-2008. *Journal of Safety Research* 51: 117-124. *These three reports address **Specific Aim 5**. This part of the aim was designed to evaluate injury and illness experiences of carpenters who performed drywall installation. The work resulted from the doctoral dissertation of Dr. Schoenfisch.*
- Lipscomb HJ, Schoenfisch AL, Cameron W: [2015] Non-reporting of work injuries and aspects of jobsite safety climate and behavioral-based safety elements among carpenters in Washington State. *American Journal of Industrial Medicine* 58(4):411-421. *This report **did not address a Specific Aim, but the analyses were planned and presented in the initial scope of work in order to supplement our knowledge of injury reporting practices and use of health insurance coverage.***
- Lipscomb HJ, Schoenfisch AL, Cameron W: [2013] Work-related injuries involving the hand or fingers among union carpenters in Washington State, 1989-2008. *Journal of Occupational and Environmental Medicine* 55(7):832-838. *This report was **not planned in the initial grant application**. At the request of the Center for Construction Research and Training (CPWR) we conducted specific analyses of work-related injuries to the hand or fingers. The analytical time was paid for by CPWR, but the costs of updating the cohort that made the analyses possible were covered under this cooperative agreement. Support from both projects was acknowledged.*

Note: **Specific Aim 1** of this project was a process aim focused on updating this occupational cohort and all the data elements including work hours, insurance eligibility, workers' compensation claims, private health insurance claims, and union local affiliations. No publications are directly tagged to this aim, but it had to be accomplished in order to proceed with the others.

Material available for other investigators

Listing of ICD-9 codes for MSDIs

- List of codes used in analyses of potential care-shifting for musculoskeletal injuries and disorders of the upper extremity and the knee.

Questionnaire

- Questionnaire sent to active carpenters 2013-2014 [available online at American Journal of Industrial Medicine Lipscomb et al., in press, 2015]

SAS CODE TO SELECT MSDIs of UPPER EXTREMITY AND KNEE FROM PRIVATE CLAIMS

NOTE:

Pri_icda2=3 digit ICD-9 code; character variable

Pri_icda=4 or 5 digit ICD-9 code; character variable

```
/*Identify UPPWER EXTREMITY MSDI claims*/
IF pri_icda2 in ('354'
                '810' '811' '812' '813' '814' '815' '816' '817' '818'
                '831' '832' '833' '834' '840' '841' '842' '880' '881'
                '882'                                '883' '884' '885' '886'
                '887'
                '912' '913' '914' '915' '923' '955')

or pri_icda in ('337.21' '711.03' '711.04'
               '715.11' '715.12' '715.13' '715.14' '715.21' '715.23'
               '715.24'
               '715.32' '715.33' '715.34'
               '715.84' '715.91' '715.92' '715.93' '715.94'
               '716.11' '716.12' '716.13' '716.14' '716.41' '716.42'
               '716.44' '716.61' '716.63' '716.64'
               '718.01' '718.02' '718.03' '718.04' '718.11' '718.12'
               '718.11' '718.12' '718.13' '718.14'
               '718.21' '718.24' '718.31' '718.41' '718.43' '718.44'
               '718.51' '718.52' '718.53' '718.54'
               '718.81' '718.82' '718.83' '718.84'
               '719.01' '719.02' '719.03' '719.04'
               '719.12' '719.14'
               '719.22' '719.23' '719.31' '719.32' '719.33'
               '719.41' '719.42' '719.43' '719.44'
               '719.51' '719.52' '719.53' '719.54' '719.62' '719.63'
               '719.64' '719.82' '719.83' '719.84' '719.85'
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               '905.2' '959.2' '959.3' '959.31' '959.4' '959.5');
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/* Identify KNEE MSDI claims*/

IF pri_icda2 in ('717' '822' '836' '844' '891')

or pri_icda in ('711.16' '711.26' '711.36' '711.46' '711.56' '711.66'
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'822' '836' '844' '891'
'924.11' '928.1' '959.7');

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**Project ID 658 - Dust-control Usage: Strategic Technology Intervention
(DUSTI)**

Final Progress Report

Grant Number: U60 OH009761-03 Project ID 658

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Abbreviations

AIHA	American Industrial Hygiene Association
ASSE	American Society of Safety Engineers
AWCI	American Wall and Ceiling Institute
CFA	Confirmatory factor analysis
DOI	Diffusion of Innovation Model
DUSTI	Dust-control Usage: Strategic Technology Intervention
FCA	Finishing Contractors Association
GFI	Goodness of fit index
HBM	Health Belief Model
IARC	International Agency for Research on Cancer
LEV	Local-exhaust ventilation
MSDS	Material safety data sheets
NSC	National Safety Council
OEL	Occupational exposure limit
OHS	Occupational health and safety
OSHA	Occupational Safety and Health Administration
PtD	Prevention through Design
PtDARM	Prevention through Design Adoption Readiness Model
PEOU	Perceived ease of use
PU	Perceived usefulness
R&D	Research and Development
SES	Self Efficacy Scale
SIC	Standard Industrial Classification
SME	Subject Matter Expert
TAM	Technology Acceptance Model
TRI	Technology Readiness Index

Abstract

Project Title: Dust-control Usage: Strategic Technology Intervention (DUSTI)

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Effective intervention strategies were developed to improve adoption of Prevention through Design (PtD) innovations in construction. PtD innovations include new designs of equipment, tools, materials, facilities, and processes, which serve to greatly reduce or eliminate occupational safety and health hazards. In this project, a ventilated sanding tool, which reduces construction dust by 95%, was the PtD innovation of interest. Five specific aims, three originally proposed and two additionally performed, were accomplished in the three-year project period.

In the first aim, a conceptual model was developed to describe and predict stakeholder readiness to adopt these technological innovations. This model was based upon three foundational conceptual frameworks: the Health Belief Model, the Diffusion of Innovation Model, and the Technology Acceptance Model. Subsequent to model development, in the second aim, survey instruments to measure the model constructs were developed and validated.

In a third aim, an intervention strategy to improve adoption readiness among construction workers was developed, implemented, and evaluated. This intervention strategy involved educational materials, hands-on training, and worksite cues-to-action. Educational materials were targeted to improve worker knowledge of the health risks associated with construction dusts. Hands-on training was developed with the objective of improving worker self-efficacy regarding the new equipment. And, cues-to-action, a technique found to be effective in community health promotion studies, were given to the workers. These cues were hard-hat stickers and t-shirts, with reminder slogans. In a pre-test/post-test experimental design, with control group (n=40), survey data were analyzed using gain-score analysis of variance and significant changes were seen in worker self-efficacy, trust-in-technology, and overall readiness to adopt the ventilated sanding tool.

The fourth project aim involved the development, implementation, and evaluation of an intervention strategy to improve adoption readiness among owners of small contracting firms. The intervention involved educational materials aimed at changing owner understanding of the risks to workers and the benefits of the use of ventilated sanding tools. A key component of the intervention involved the creation of 'technology champions' within the firms. Prior work in the Diffusion of Innovation field has found that technology champions within an industry are of critical importance in the diffusion of a new innovation within the industry. In a pre-test/post-test experimental design, with control group (n=40), survey data were analyzed using gain-score analysis of variance and significant changes were seen in firm owner perceptions of risk, trust in technology, perceived ease of use, perceived usefulness, and overall readiness to adopt the PtD innovation.

And, in the fifth project aim, an intervention to improve adoption within large construction firms was similarly developed and evaluated. This intervention strategy employed web-based information dissemination. It aimed to communicate productivity, risk, and effectiveness information about the ventilated tool to purchasing agents at large firms. Significant results were found regarding risk perception, perceived ease of use, and perceived usefulness. However, there was no significant change in trust in technology or readiness to adopt the PtD innovations.

This project developed successful strategies for improving construction industry use of technologies which reduce risk. The conceptual model, survey instruments, and intervention strategies should prove useful to occupational safety and health professionals, construction managers, and future researchers.

Section 1: Final Progress Report

Key Findings

Theory-based intervention strategies were found to be effective in improving worker and contractor willingness to use ventilated tools. The most impactful intervention methods included: training regarding risks to worker health, hands-on training with ventilated tools, cues-to-action reminders to work safely, and the development of ‘technology champions’ within the contractor community. The technology champions were created by allowing contracting firm owners to use the ventilated tool, free of charge, for a month. Once they had the experience of using the tool in daily work operations, the majority became enthusiastic champions of the tools and expressed willingness to change their work methods and to communicate about the tool to their peers in the construction industry.

Workers who went through the intervention expressed enhanced self-efficacy, trust in the ventilated tool, and willingness to use the tool in future work operations. Contractors who participated in the intervention demonstrated improved understanding of the risk of construction dust to workers, perceived ease of use and usefulness of the ventilated tool, and increased willingness to use the ventilated tool in future work operations. One of the most important aspects of the intervention strategies was the opportunity to experientially learn about the tool: to use it in actual work operations. The interventions for the workers and small contracting firm owners allowed for actual use of the tool. These interventions saw the greatest impact on participant opinions. The large contracting firms participated in web-based learning only. Even though they watched videos of the tool being used in work operations and a video of a contractor discussing the benefits of the tool, these participants did not experience major changes in opinion regarding their willingness to use the tool.

Survey instruments were developed and tested to ensure that they reliably and accurately measure the theoretical constructs of interest. A theory-based conceptual framework was developed, based on a body of previous research in health promotion and technology innovation diffusion. Time and motion analysis demonstrated that ventilated sanding tools significantly improve work through-put and productivity, along with reducing the health risks to workers.

Web-based methods of information dissemination were not found to be as effective as in-person and hands-on approaches. More work is needed to improve this mode of intervention.

Translation of Findings

The findings of this work can be directly applied to improve construction safety and health. To improve worker and contractor willingness to use safety equipment, training interventions can be developed based on the findings of these studies, in the following ways. Training should emphasize the health risks associated with the work. Workers should be provided with hands-on training, until they become comfortable with the use of the new equipment. Contractors, if allowed to use the new equipment for a trial period in their actual work operations, are far more likely to become champions of the equipment, acquire it for their own use, and promote its use to others in their trade. Cues to action – visible reminders to use the new equipment – are also

effective methods of improving worksite compliance regarding the use of new safety equipment. And, lastly, web-based training alone is not as effective as training which allows for experiential learning.

The findings of this work can also inform future research investigations in several ways. The Prevention through Design Adoption Readiness Model (PtDARM) can be used in future studies of intervention design, innovation diffusion, and health and safety behavior change. The validated survey instruments can be employed as data collection tools by researchers engaged in health and safety behavior research. And, the intervention strategies found to be effective in the current work can be applied to other PtD innovations, other construction trade sectors, and other occupational health and safety hazards.

Outcomes/Impact

1) Potential Outcomes

The findings of this work could improve construction safety and health in construction practice in the following ways:

- Development of worker training guidelines
- Improved worker training
- Improved adoption of PtD innovations among workers and contractors

2) Intermediate Outcomes

The findings of this work have the potential to improve construction safety and health management:

- Safety management programs should incorporate the findings of this work
- The American Wall and Ceiling Industry has published these findings in their trade publication
- The trade journal, Professional Safety, has accepted an article for publication, thus disseminating this work to safety professionals
- Future research is currently underway to develop similar interventions for concrete, masonry, welding, and asphalt roofing trade sectors
- Technology champions are critically important to improve PtD dissemination

3) End Outcomes

The DUSTI project has begun to see some notable impacts:

- The Occupational Safety and Health Administration (OSHA) cited this work in its recent advisory document regarding the control of silica in construction operations.
- Environment Canada has cited this work in a draft regulation regarding quartz exposures.
- The PI was invited to speak at Purdue University's annual event, "The Engineer of 2020" on PtD in engineering design.

Section 2: Scientific Report

Background

Prevention through Design (PtD)

The optimal method of preventing occupational illnesses, injuries, and fatalities is to “design out” the hazards and risks; thereby, eliminating the need to control them during work operations. This approach involves the design of tools, equipment, systems, work processes, and facilities in order to reduce, or eliminate, hazards associated with work. Prevention through Design (PtD) has been defined by Schulte et al. (2008) as:

The practice of anticipating and “designing out” potential occupational safety and health hazards and risks associated with new processes, structures, equipment, or tools, and organizing work, such that it takes into consideration the construction, maintenance, decommissioning, and disposal/recycling of waste material, and recognizing the business and social benefits of doing so.

The PtD movement saw its genesis in the early 1990’s, with the formation of a committee within the National Safety Council (NSC) to study the feasibility of incorporating hazard reduction into design procedures. The outcome of this early work was the formation, in 1995, of The Institute for Safety through Design, with membership from industry, academe, organized labor, and other interested parties (Manuele, 2008). Seminars, workshops, and symposia were held throughout the late 1990’s and early 2000’s. In 2006, the Australian government issued a guideline on the *Principles for Safe Design for Work*, and in 2007 a special edition of *Safety Science* was published on “Safety by Design”. Also in 2007, the OSHA Construction Alliance Roundtable Design for Construction Safety Group developed a short course entitled, “Design for Construction Safety” and the Institute of Mechanical Engineers held a workshop entitled, “Risk Education for Engineers” (Manuele, 2008). One of the goals of the latter was to advance the understanding of the importance of educating undergraduate engineers in risk assessment techniques.

In 2008, the National Institute for Occupational Safety and Health (NIOSH) launched a national PtD initiative; calling on all major industrial sectors to emphasize hazard mitigation at the design stage of tools, facilities, and work processes (Schulte et al, 2008). NIOSH partnered with the American Industrial Hygiene Association (AIHA), the American Society of Safety Engineers (ASSE), Kaiser Permanente, Liberty Mutual, the National Safety Council (NSC), and the Occupational Safety and Health Administration (OSHA), in the development of a *National Initiative on Prevention through Design*, launched in a 2007 workshop and published in a special edition of the Journal of Safety Research in 2008 (Howard, 2008).

One conclusion of the 2007 workshop was that business decision makers, including those who purchase products and services, will need to establish a demand for such PtD designs. The PtD Initiative aims to focus “both on the supply of innovative design solutions and on creating a demand among business decisions makers who will value and request them” (Howard, 2008). Therefore, the work described in this paper aims to address this gap through advancement of our

understanding of factors underlying and influencing PtD supply and demand and through development of a model to predict “adoption readiness” among key construction stakeholders: the workers and owners of small and large firms. The work described herein, the development of a PtD Adoption Readiness Model (PtD ARM), is part of a larger research initiative in which model-based intervention strategies are being developed and evaluated.

Because of the low rates of adoption of PtD innovation within the construction industry, the present work sought to develop a conceptual framework that will describe the constructs of importance in enhancing adoption readiness within that sector specifically. This framework was based upon previous findings regarding the barriers that are preventing widespread innovation diffusion, as described below.

PtD in Construction

In the construction sector, the term “design” is most commonly applied to the process of designing the end-product to be constructed: the building, facility, or infrastructure component. However, PtD has a broader definition and applies to the design of all tools, equipment, materials, and work processes that are employed during the construction process; as well as to the design of the constructed environment itself. Therefore, hazard reduction can be accomplished via a multitude of means; such as, changes in tool selection, material composition, work process management, or facility design. Much of the work done, to date, in PtD in the construction sector has emphasized the reduction of risk in the domain of occupational safety. Occupational safety risks are those that can cause injury or fatality in the event of an accident. This section briefly reviews the body of scholarly work in that domain. One gap in the existing construction PtD literature is in the realm of reduction of occupational *health* risks. Occupational health risks are those that cause disease or disability in the exposed worker population. Major construction occupational health risks and appropriate PtD strategies will be reviewed in subsequent sections of this paper.

PtD to reduce construction occupational safety risk has received attention in the scholarly literature since the early 1990’s. A pivotal article by Hinze and Wiegand (1992) found that only one third of design firms factored construction worker safety into the design process. Predominant hazards addressed by those firms factoring safety into design were excavation/trenching and fall risks. Concerns over liability were identified as a major barrier to diffusion in the design community. The Construction Industry Institute conducted a study in the 1990’s to assess and enumerate construction “best practices” for PtD. This study led to the development of a tool entitled “Design for Construction Safety ToolBox” (Gambatese et al, 1997).

The United States is said to lag behind other developed countries in the diffusion of PtD innovation and adoption of PtD approaches within construction (Toole and Gambatese, 2008). These concepts have been widely accepted throughout the European Union and Australia. Barriers to the diffusion of PtD had been encountered by these countries and lessons can be learned from their experiences. Toole (2005) makes the case that liability concerns may be a larger barrier to PtD adoption in the U.S., due to the litigious nature of the business climate in that country. Toole and Gambatese (2008) identify four key aspects of PtD for emphasis in the

near future as the construction industry moves toward embracing a PtD approach. These four focus areas are: increased prefabrication, reduced use of hazardous materials and systems, increased application of construction engineering, and enhanced spatial consideration.

Several large engineering/construction firms attended the 2007 National PtD Initiative Workshop; including Jacobs Engineering, Bechtel, Washington Group, BE&K, Southern Company, Haskell, and Parsons (Behm 2008). Behm (2008) reports that many of these large firms have been proactive in investigating and implementing PtD strategies, but states that industry-wide diffusion of PtD innovation is currently poorly documented and that a clearinghouse of “best practices” is needed. The current article aims to address this gap by providing “best practice” PtD solutions for addressing occupational health risks, with special emphasis on three of the most pressing health hazards presently known to the industry.

PtD for Construction Health Hazards

Occupational health risks arise when workers are exposed to chemical, biological, or energetic hazards that might lead to resulting short-term illness, long-term chronic disease, fatal disease, or diminished wellness. Chemical hazards include solvents, finishes, compressed gases, and particulates (e.g.: silica, asbestos, fumes from welding/cutting). Biological hazards include disease-causing microorganisms and allergens. Energetic hazards encompass such agents as noise, vibration, electromagnetic energy and fields, and ionizing radiation. The present section will review a few of the most notable chemical hazards associated with construction work operations and will present PtD approaches to reducing or eliminating these risks.

PtD approaches to reducing occupational health risk from chemical hazards fall into three major categories: material substitution, isolation, and process re-design (Table 1). Material substitution approaches generally involve selection of less-toxic materials in the place of those with higher toxicity. The construction industry has already experienced several cases of successful material substitution design solutions; such as, the use of man-made mineral fibers in the place of asbestos-containing materials, the use of non-lead paints rather than lead-containing paints, and recent reformulations of finishes to reduce the volatile organic compound components. Isolation solutions are adopted to either isolate the hazardous process or to isolate the workers, as in the case of an enclosed and ventilated equipment cab. Process re-design approaches can be further divided into three categories: wet methods, local exhaust ventilation systems, and work process changes. Wet methods are employed to suppress the generation of particulate health hazards, in various applications (Figure 1). Local exhaust ventilation is a type of ventilation system that removes the hazard at the point of generation, before it has a chance to become entrained in the ambient air and inhaled by workers (ACGIH, 2007). In construction, the most useful local exhaust ventilation is in the form of ventilated tools. Ventilation systems are integrated into construction tools and equipment, to capture contaminants and prevent worker exposure and environmental contamination. Work process changes are adopted to reduce the amount of time a worker is exposed to a hazardous chemical. These changes can involve worker rotation, automation, or prefabrication.

Table 1. Prevention through Design (PtD) Solutions for Chemical Hazards

PtD Solution Category	Examples for Construction Industry
Material Substitution	MMMF for Asbestos Limonene for Chlorinated Hydrocarbons Latex Paint for Lead Paint Alkaline Copper Quaternary (ACQ) for CCA Low-dust mud for traditional drywall mud Phenol formaldehyde – “low emitting” paint Garnet, glass beads, or iron oxide for silica-sand in sandblasting
Process Re-design	
Wet-methods	Vehicle-mounted rock drilling rigs Concrete cutting Brick cutting Pneumatic hand-operated grinders Jackhammers
Ventilation	Ventilated drywall sanding tool Ventilated concrete sanding tool Ventilated masonry saws
Isolation	Asphalt paver enclosed cab Ventilated enclosure surrounding masonry saw Vehicle-mounted rock drilling rig operator cab
Work Process Re-design	Automation Panelization and prefabrication Worker rotation



Figure 1. Example of wet method: drilling without (above) and with (below) water

Specific Hazards and PtD Solutions

The remainder of this paper reviews literature concerning some of the highest-risk construction activities for worker exposure to chemical health hazards and presents evidence of effectiveness of corresponding PtD solutions for mitigating those risks. Masonry operations, asphalt roofing, and welding are associated with some of the most pressing occupational health hazard risks in construction. PtD solutions do exist to control the hazards associated with these construction operations. In the sections that follow, the occupational health hazards associated with these activities, along with their PtD solutions and gaps in the currently available PtD design options, are described in detail.

Concrete and Masonry Hazards

Concrete and masonry operations have been found to generate dust that contains respirable quartz. Many construction materials employed in the construction industry contain quartz: brick, mortar, concrete, slate, dimensional stone (granite sandstone), stone aggregate, tile, asphalt filler, roofing granules, soils, wallboard, joint compound, plaster, putty, and sand used for blasting (OSHA 2009). Quartz (crystalline silica) has well-documented effects on the human respiratory system and has been associated with silicosis, a fibrotic disease of the lung; increased incidence of tuberculosis; and malignant neoplasm of the lung (Knutsson et al, 2000). The International Agency for Research on Cancer (IARC) has classified quartz as a “group I human carcinogen,” a classification indicating that sufficient evidence of causality exists in the scientific literature (IARC, 2003). The construction industry has the highest rate of silica-related occupational fatality among all industrial sectors (Linch et al, 2002). An estimated 800,000 U.S. workers are employed in the Standard Industrial Classification (SIC) code group 174: Masonry, Stonework, Tile Setting, and Plastering. A 1998 examination of OSHA data suggests that this occupational category may have more workers at risk of silica exposure than any other SIC code group (Linch et al, 1998). This study estimated that more than 132,000 masonry workers and more than 118,000 concrete workers are potentially over-exposed to respirable silica, annually. Tools such as pneumatic hammers and drills, power saws, grinders, chippers, and mills are used frequently in these trades. In a comprehensive industrial hygiene assessment of construction worker chemical exposures, Verma et al. (2003) found that airborne particulate matter was the most prevalent hazard class. In this study of 1,265 task-based assessments, the authors found that dust affects not only the workers involved in direct exposure-causing tasks, but also those performing ancillary activities. Construction tasks evaluated included framing, bricklaying, excavating, foundation building, interior carpentry, insulating, dry walling, painting, and plumbing. Those tasks associated with the highest dust generation were drywall and concrete operations. A study of exposure to silica dust in the U.S. construction industry found that “silica exposures are grossly unacceptable” (Rappaport et al, 2003). Personal sampling was performed for workers in the following trades: bricklayers, abrasive blasters, and laborers. Mixed models were fitted to the log-transformed air levels to estimate the means and variance components of the distributions in each trade. Probabilities of over-exposure were estimated between 64.5 and 100% for silica and between 8.2 and 89.2% for other dust. The authors stated that engineering and administrative controls are needed to reduce worker exposures. The authors concluded that urgent action is

needed to address silica over-exposure in the construction industry. The following masonry and concrete operations have been associated with overexposure to respirable silica: surface grinding, saw-cutting concrete, drilling concrete, demolishing, tuck-point grinding, clean-up, concrete mixing, and sack and patch (Flanagan et al, 2003). Studies on the use of handheld masonry saws to cut bricks and concrete blocks found that operators were exposed to silica levels as high as fourteen times the OSHA occupational exposure limit (OEL) of 0.1 mg/m^3 (OSHA 2009).

PtD Approaches to Concrete and Masonry Hazard Control

Several PtD control options are available for the reduction of dust generation during concrete and masonry activities. General categories include: local-exhaust tool-mounted ventilation, wet methods, isolation, and sweeping compound for clean-up activities.

Local-exhaust ventilation systems exist for many of the silica-exposing construction operations. Cutting, grinding, and sawing tools can be equipped with local-exhaust ventilation (LEV), which has been found to be very effective (Akbar-Khanzadeh et al, 2001). Ventilated stationary masonry saws are commercially available and have been found to effectively reduce worker exposures to dust (Croteau 2000). Under experimental conditions, a fixed-blade masonry saw ventilation system was found to reduce dust levels by 80 to 95 percent (Croteau et al 2002). Handheld masonry saws can be equipped with vacuum dust collection systems and can be effective at controlling worker exposures. Studies have found these systems to result in reductions of 88 percent (Thorpe et al 1999); however, the exterior hood design employed in the study is yet to become commercially available. A study by Croteau (2002) found that a commercially available system required redesign in order to effectively control the respirable dust from handheld masonry saw operations. Therefore, additional design work is required to improve PtD ventilation systems for handheld masonry saws. Vacuum dust collection systems for hand-operated surface finishing grinders can significantly reduce operator exposures to silica; however, current designs have not been found to reliably keep levels below OSHA limits (OSHA 2009). Re-design efforts to improve ventilation systems for these grinding tools are a suggested area of future research and development, as the ventilation systems have some advantages over wet-methods. Handheld angle grinders used for renovation of deteriorating mortar (tuckpointing/mortar removal) are associated with high operator exposures to respirable silica (Lyons et al 2007; NIOSH 2000). Ventilation systems are readily available for use with these tools; however, they are not widely used in practice (Lyons et al 2007). These systems include a shroud, which surrounds the grinding wheel, and a vacuum to pull air through the shroud. Studies have suggested design flaws in currently available angle grinder ventilation systems, both in terms of usability and effectiveness (OSHA 2009). Additional research is needed to improve industry adoption of this PtD solution for tuck-pointing risks. Rotary hammers and similar tools employed to drill small-diameter holes in concrete and other masonry materials can expose employees to hazardous levels of respirable silica dust (Lofren, 1993). Operations with these tools are associated with exposures exceeding three times the OSHA OEL. Ventilated tools can significantly reduce risk and are commercially available for handheld drills. These systems enclose the drill bit in a suction ring, which includes a port for attaching a vacuum collection system. These systems have been found to be highly effective, reducing dust by as much as 90 percent (Sheperd et al 2009)(Heitbrink and Watkins 2001).

Wet methods, the wetting of the substrates before or during abrasive operations, have also been found to be effective dust control solutions (Akbar-Khanzadeh et al, 2007). Wet methods are the most effective solution for the control of silica dust during the use of stationary masonry saws. A study of saw operators found exposures to be routinely below 0.1 mg/m^3 , and usually below 0.05 mg/m^3 (NIOSH 1999a). Most stationary saws come equipped with integral wet-method systems. Water-fed handheld saws that are gasoline-powered, air-powered, electric-powered and hydraulic-powered are commercially available. Water can be supplied to the saws either with a pressurized portable water supply or with a constant water source, for example, a municipal water supply. Wet cutting is the most effective method for controlling silica dust during the use of handheld saws (Thorpe et al 1999). Dust levels are reduced by 94 percent for pressurized portable water supply systems and up to 96 percent for constant supplying water sources (Thorpe et al 1999). A reduction of 96 percent resulted in time-weighted average operator exposures of 0.06 mg/m^3 , a level below the OSHA OEL. Wet methods are available for hand-operated masonry grinders used for surface finishing and cutting slots. Handheld water-fed grinding equipment is commercially available for concrete applications, granite grinding, and polishing operations. Also, conventional grinding equipment can be retrofitted to add a water-feed capability (OSHA 2009). Wet methods consistently keep operator exposures to silica below OSHA limits (Simcox et al 1999). Wet methods are not employed during tuck-pointing operations with an angle grinder, since the addition of water would result in work quality problems. Although not commercially available at the time of this article, an effective means of controlling dust during jackhammer operation, however, is wet-methods. Zalk (2002) found a reduction in silica dust levels from 50 to 98 percent, when workers operated jackhammers with 1/8 gallon per minute water discharge from a retrofitted 90-lb jackhammer. In current practice, manual wetting of surfaces is employed. However, additional research is needed to further develop water-fed jackhammers, with integral water-supply and distribution mechanisms. Wet methods are generally not appropriate for use with electric rotary hammers, but are available for pneumatic drills. Water-fed pneumatic drills are commercially available, typically marketed for work in explosive atmospheres. These devices have been found to reduce silica exposure risk (CS UNITEC, 2003).

Isolation designs exist for mitigation of some silica-related risks. Enclosure systems for stationary masonry saws have been found to be effective at preventing worker dust exposure, but are not widely available commercially (OSHA 2009). While isolation systems are commonly employed for heavy equipment operations, they remain impractical for most portable hand-operated construction tools.

Sweeping compound is a relatively new PtD solution for the control of worker exposure to dust during clean-up activities on a construction site. Sweeping compound is composed of dyed sawdust, sand, and mineral oil and is broadcast over the floor before sweeping. The added surfactant molecules have a high affinity for most other materials and tend to agglomerate with the dust particles, leading to higher weight-to-surface area ratios and lower tendencies to stay airborne (Westbrooke 1999).

Barriers to PtD Adoption

Much of the research on innovation in the construction industry has focused on the barriers to adoption (Slaughter, 2003). Adoption of innovations in construction has been defined as a firm's use of a technological innovation in at least 25% of the cases in which it has an opportunity to use it. Industry barriers to adoption include, market changes, negative perceptions of innovation, and inflexible performance standards. Frequent downturns in the construction market may deter firms from adopting innovations (Blackley and Shepard, 1996). Regulatory bodies in construction can also have an impact on the successfulness of innovations. The development of new products or processes in construction is not always welcomed by all parties (Oster, 1977). Building codes and construction regulations often serve as constraints or drivers of innovations (Manseau and Shields, 2005). Stringent standards for product performance, safety and environmental impacts can create pressure for firms to innovate, improve quality, and upgrade technologies (Gann et al, 1998). Unions may resist innovations that are viewed as labor saving or eliminating products or processes (Blackley and Shepard, 1996).

Cost, risks, uncertainty and limited control over the way construction work is performed and the products that are chosen make diffusion of innovation in the construction industry difficult (Blackley and Shepard, 1996). Barriers that affect the implementation of innovations also include contract issues, the cost of research, lack of information about available innovation, and lack of awareness of potential cost savings of adoption (Ling, 2003). Evidence that products and processes will provide an advantage over existing methods and products can serve as a driver for adoption. A study by Toole (1998) found that builders become more likely to adopt a product if they have witnessed that product in successful use elsewhere. Builders are frequently unwilling to adopt innovations because of concern over risk and lack of awareness of benefits (Manseau and Shields, 2005).

One significant barrier to adoption for safety and health innovation in the construction industry is a lack of knowledge of health risks (Kramer et al, 2009). The lack of understanding that hazards exist or that controls are available can influence the decision to adopt. Managers tend to devote more attention to items that are failing than to those that are meeting their targets (Mitropoulos and Tatum, 1999).

In a study of technology-adoption barriers from the worker perspective, drywall-finishing workers participated in semi-structured, in-depth personal interviews (Young-Corbett et al, 2010). Attitudes and perceptions toward dust-control technologies were solicited and emergent themes were explored. The HBM served as the framework for understanding workers' readiness to adopt control technology. Workers tended to perceive a risk to health associated with the dust; however, assessments of personal susceptibility to disease were low. Identified barriers to adoption were organizational factors and self-efficacy. The participants expressed little confidence that management would value worker health and reported a perception of having little personal control over the decision to adopt this technology.

In a study of owner perspectives on dust control, a telephone survey was conducted to identify barriers to technology adoption and to explore firm owner perception of risk (Young-Corbett and Nussbaum, 2009). Barriers associated with technology usability, productivity, and cost were

identified. Additionally, a misperception of the risk to worker health was interfering with motivation to adopt the PtD innovations.

Research by Koebel (2003) has documented the complexity of innovation diffusion in the construction industry. Several industry characteristics are considered impediments to innovation, particularly: site variability, the “one-off” project character of most building construction jobs, regulatory climate, industry fragmentation and decentralization, a low level of research and development (R&D) investment, boom-bust business cycles, and the position of construction companies in the supply chain (Koebel, 2003)(Koebel, 1999). Key factors influencing diffusion can vary across firm size, including the role of champions and the information channels influencing diffusion.

Although prescriptive building codes are often perceived as impediments to innovation in construction, governmental regulations can be very instrumental in influencing innovation adoption and diffusion, but the impacts are complicated and sometimes have opposing effects (Baldwin and Cave, 1999). The traditional model of regulation frequently mandates adoption of specific health and safety practices or adherence to standards of performance. The long history of automotive safety innovations points to the co-evolution of regulatory mandates and safety innovation diffusion (Leonardi, 2010). Jensen, Halvorsen and Shonnard (2011) found that effective federal energy policies include both incentives and impediments for the adoption of lignocellulosic ethanol as a low carbon fuel source. In the macroeconomic literature on induced innovation, regulations impacting factor prices are expected to induce innovations in response to prices. Jaffe and Palmer (1997) found that regulatory compliance costs had the expected positive effect on patenting of environmental technologies by industry. Taylor, Rubin and Hounshell (2005) also found that regulatory stringency induced innovation and diffusion of sulfur dioxide control technologies; Kammerer (2009) reported similar results for environmental product innovation among appliance manufacturers in Germany. Bossink (2004) found that government regulations and incentives were drivers of innovation in construction networks in the Netherlands whereas ‘market-pull’ from the building owner did not induce construction innovations. The timing, character and composition of regulations, including the mix of mandates and incentives, are likely to be important in the diffusion trajectory of PtD health and safety innovations in the construction industry.

In a study of two national surveys of innovation adoption in the residential construction sector, factors affecting technology adoption by small and large firms were identified. Small builders were found to be more receptive to innovation and the influence of key “technology champions”(Koebel, 2008)(Baldwin and Cave, 1999). Demonstration projects that introduce new technology to owners of small firms were found to convert these builders into champions of the innovations. In large-scale production residential building firms, it was found that technology-adoption decisions were more likely to be made by purchasing units of the organization. Therefore, the technology champion model had less impact in this sector. The study suggested that these larger firms should be targeted with information about affordability, efficiency, and productivity of innovations to increase adoption and diffusion within the large-scale residential construction sector.

Adoption Readiness

Adoption Readiness has been defined as a “state-of-mind about the need for an innovation and the capacity to undertake technology transfer” in a comprehensive review of the literature on the subject (Armenakis et al, 1993). It is the cognitive precursor to “behaviors of support” for the actual transfer effort. Individual and organizational readiness for change are said to involve beliefs, attitudes, and intentions regarding; 1) the extent to which changes are needed, and 2) the level of capacity available to make the requisite changes. Adoption readiness is the first phase in the “natural cycle of change” model advanced by Lewin (1947). Defining readiness for change in this way has two important implications for the design and implementation of technology transfer interventions: readiness can be enhanced, and it can be assessed (Kanter, 1983). Readiness for change is not a fixed element of individuals or systems. It may vary due to changing external or internal circumstances, the type of change being introduced, or the characteristics of potential adopters and change agents. Thus, interventions to enhance readiness are possible and can increase the overall success of technology transfer (Backer, 1995).

Diffusion of Innovation

Diffusion of innovation is the process through which an innovation, whether an idea or product, is communicated over a period of time in a social system and involves some degree of uncertainty (Rogers 2003). Innovation is defined as a significant improvement in a product, process or system that is actually used and which is new to those who will be developing or using it (Manseau and Shields 2005). One of the necessary components of an innovation is the ability of the innovation to improve some aspect of the adopter’s performance of a work task (Toole 1998). Two important factors that are involved in the diffusion of innovation are the discovery of the innovation and the diffusion of it (Ball 1999). Diffusion involves communication about the innovation to the target adopters (Koebel 1999). Four main elements compose the general diffusion model as outlined in Rodgers 5th Edition of Diffusion of Innovations (2003) include: the innovation, communication channels, time, and a social system.

An **innovation** could be any idea, product, process or object that is perceived as new to an individual or group (Rogers 2003). Innovation can take many forms and can be incremental, in which small changes occur based on current experience, radical, where a breakthrough in science or technology provides a new change, or modular, where there is a change in concept within a component of a larger system (Blayse 2004). For a product, process or idea to be considered an innovation, it does not need to be something new pertaining to the time when it was created, but rather the newness of the innovation can be measured if it is new to the individual or adopting unit. The newness of an innovation is often gauged on a person’s knowledge, or decision to adopt (Rogers 2003). The characteristics of innovation that are the most responsible for influencing adoption are:

- a. Relative advantage- Relative advantage is perception that the innovation is better than the idea, product or process that already is in use by the potential adopter. If a potential adopter can readily see the benefits of using an innovation there is greater likelihood for adoption. The greater degree the adopter perceives the advantage, the more likely they are to adopt.

- b. Compatability- Compatability is the degree to which an innovation is perceived as being consistent with the needs of the potential adopters. Adopters are looking for products they can incorporate into their systems without much effort and without having to change values.
- c. Complexity- Complexity is the degree to which the potential adopter views the innovation in terms of how difficult the innovation is to understand or the ease of use of the innovation. If an innovation is easy to understand and use then the likelihood of adoption increases.
- d. Triability- Triability of an innovation is the opportunity given to use an innovation on a trial basis before wholly committing to adoption.
- e. Observability- Observability is the visible results of the innovation in practice. If observers can readily see the results of an innovation, the likelihood of adoption increases. (Rogers 2003)

Any of these five characteristics could aid in innovation adoption and if aspects of these elements are not met, the missing pieces could represent barriers to adoption of innovation.

Communication channels are the second main element of diffusion. Diffusion of innovations is facilitated by tapping into many sources of communication and information (Toole 1998). Diffusion is the information exchange through which an innovation is communicated to others. The process of communication through diffusion includes the innovation, an individual or group that has experience using the innovation or a knowledge of the innovation, an individual or group who does not yet know about the innovation or has not experienced it, and a way for these two parties to communicate with each other (Rogers 2003). Many methods of communication are available for use in the diffusion process including the use of mass media, inter-organizational networks, educational institutes, research institutions, and professional associations (Sexton 2004). Different kinds of communication channels have differing effects on the diffusion process and rate of adoption. Mass media provides an efficient channel for communication while interpersonal interactions remain the most important channel for providing information about innovations and influencing the adoption process (Lin 1975; Rogers 2003).

Time is a third element of diffusion of innovations. Time is a variable that is used to measure the rate of diffusion of an innovation and is one of the strengths of the diffusion of innovation model. Time is involved in diffusion in three major functions. The first is in measuring the time that passes from the time knowledge of an innovation is introduced to an individual or group and the time they adopt or reject the innovation. The second function time is the time in which an innovation is adopted by an individual or group in relation to the introduction of the innovation into society. For example a person can adopt in the early introduction stages of an innovation or can wait and become a late adopter after seeing others adopt the innovation and use it successfully. A common element of the Diffusion of Innovation model is the graph of Everett Rogers for Technology Adoption Lifecycle that shows the distribution of adoption in relation to time shown in Figure 2. The third function of time in the innovation process is the rate of adoption showing the number of members in a system that adopt the innovation in a given time period (Rogers 2003).

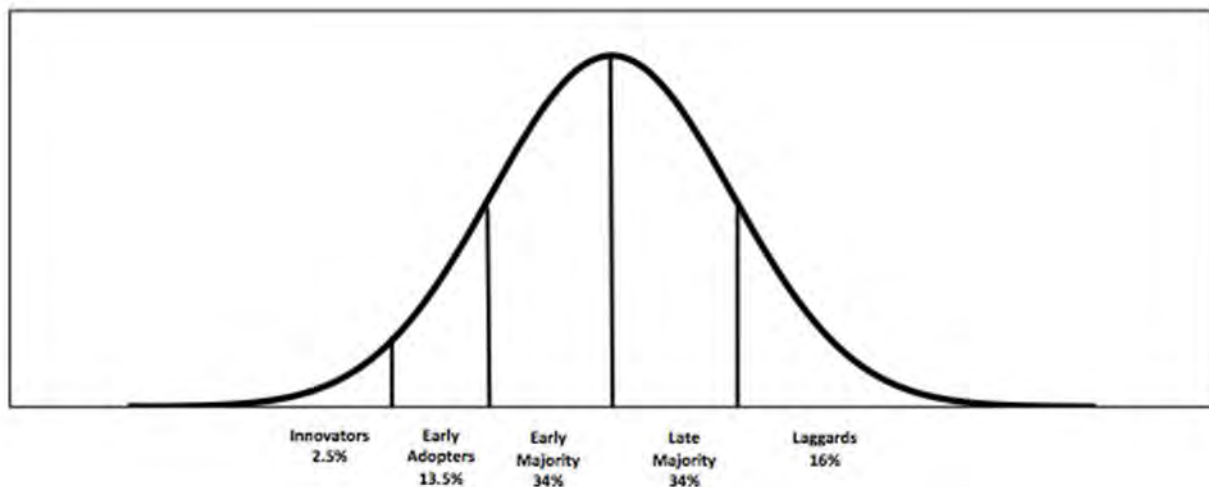


Figure 2. Bell Shaped Graph Depicting Levels of Adopters (Adapted from Rogers 2003)

Social systems are the fourth element of diffusion of innovations. Social systems could be individuals, groups or members of organizations. The social system affects the diffusion of an innovation depending on the social system structure, processes, roles of members, types of innovation decisions and the consequences of adoption (Rogers 2003). The social system has normal patterns of behavior that may serve as a barrier to adoption for innovation. The normal patterns or processes in the social structure let an individual know what is expected. The roles of individual members of a social system also have an influence on diffusion of innovation. Innovative individuals known as opinion leaders or change agents are able to influence other individuals attitudes and behaviors (Rogers 2003). These opinion leaders also often referred to in innovation discussions as champions can come from formal leaders or informal leaders in a social system (Howell and Higgins 1990; Markham 2001). Social systems can also influence the adoption of innovation by deciding to adopt innovations by collective or authoritative decisions. Decisions to adopt innovations in a social system may be optional decisions that are left up to an individual, or collective decisions, which the decision to adopt or reject innovations is based on the consensus of the group. Social systems might also affect the adoption of innovations through the use of authority innovation decisions in which the decision for adoption lies with a few individuals who possess power. The fastest rate of adoption comes from authoritative decisions (Rogers 2003).

Diffusion in Construction

Innovation in construction offers potential for significant company, social and industry benefits (Slaughter 1998). The construction industry has been viewed as an industry that is resistant to technology and slow to adopt new innovations (Koebel 1999). Innovation occurs in construction more than what is recognized by those outside the construction industry. A lot of the innovations done in construction are done by people working on site as opposed to large manufacturers (Slaughter 1993). The importance of innovation in the construction industry is recognized as a means to improve the quality of life, productivity and safety (Arditi et al. 1997). The amount of

information presented to the potential adopter can greatly influence the decision to adopt. Innovations can be categorized into high uncertainty and low uncertainty innovations. High uncertainty innovations are those in which potential adopters are missing substantial information relating to, for example, long-term performance, total installed cost, safety, and acceptance by customers. Low uncertainty innovations are those for which potential adopters are missing relatively little information pertaining to these criteria (Toole 1998).

Barriers to Adoption in the Construction Industry

Much of the research on innovation in the construction industry has focused on the barriers in the industry (Slaughter 1993). Adoption of innovations in construction has been defined as when a firm uses a technological innovation in at least 25% of the cases in which it has an opportunity to use it (Slaughter 1993). Frequent downturns in the construction market may deter firms from adopting innovations (Blackley and Shepard 1996). Regulatory bodies in construction can also have an impact on the successfulness of innovations. The development of new products or processes in construction is not always welcomed by all parties (Oster 1977). Building codes and construction regulations often serve as constraints or drivers of innovations (Manseau and Shields 2005). Stringent standards for product performance, safety and environmental impacts can create pressure for firms to innovate, improve quality, and upgrade technologies (Gann et al. 1998). Unions may resist innovations that are viewed as labor saving or eliminating products or processes (Blackley and Shepard 1996).

Cost, risks, uncertainty and control over limited aspects of the way that construction work is performed and the products that are chosen makes diffusion of innovation in the construction industry difficult (Manseau and Shields 2005). Barriers that affect the implementation of innovations also include forms of contracts, the cost of research, lack of information about the innovation or being unaware that one exists and not realizing the potential cost savings of adoption (Ling 2003). Many of those in the construction industry are looking for proof that products and processes will provide an advantage over existing methods and products. A study by Toole found that builders want to see someone else use the product and be successful before they are willing to try it for themselves (Toole 1998). Builders are frequently unwilling to adopt innovations because of the risks that fall on the builder without capturing the benefits (Manseau and Shields 2005).

One significant barrier to adoption for safety and health practices and methods in the construction industry is that there is a lack of belief among the users that a hazard actually exist or they lack the confidence that they are able to control the hazard (Kramer et al. 2009). The lack of understanding that hazards exist or that controls are available can influence the decisions of managers. Managers tend to devote more attention to items that are failing than items that are meeting their targets (Mitropoulos and Tatum 1999). If a manager doesn't perceive there is a problem then they are unlikely to adopt innovations.

Communication

Communication channels can be used in the construction industry to increase adoption of innovations. Construction safety innovations including drywall dust-control innovations face

obstacles due to the limited knowledge of the innovation and the benefits it may provide (Nooteboom 1994). Potential adopters of innovations in construction are missing a tremendous amount of information (Toole 1998). In the diffusion model, communication is distributed in different ways. Information concerning the benefits of the usage of dust-controlling drywall sanding tools could be achieved through training and re-training courses, as well as training manuals or distributed informational materials (Gherardi 2000). Diffusion of innovation can not be achieved unless others transfer knowledge and diffuse information about innovations to others (Peansupap 2005). Knowledge and competence are key elements that influence the personal safety performance of construction workers (Langford 2000).

Time

Time is used in the diffusion model to understand the rate of adoption of innovations. The time an innovation is introduced to the time it is adopted can be the result of how ready to adopt the firms may be (Rogers 2003). Construction innovations tend to face obstacles that delay the diffusion of innovation due to liability, regulatory codes and the lack of information (Manseau and Shields 2005). When presented with innovations, people may expect that something better will come along shortly so they wait and watch the experience of others before adopting which is a retarding factor in the time element of diffusion (Ball 1999). The relative newness of dust-control tools may have an effect on the adoption rate among drywall companies. As time goes on and information increases diffusion is expected to increase.

Social System

Diffusion of innovation in construction firms requires addressing the social system of the industry. The norms of a social system are the established patterns of behavior for the members of the system. Norms set the standard and relate to individuals what behavior is expected (Rogers 2003). Introducing changes into a construction social system can create ripple effects that can be difficult to anticipate (Manseau and Shields 2005). The culture of a company can play an important role in the adoption of innovations within a social system and innovations should try to be compatible with the normal behaviors that are in place. Structural barriers such as building codes, and construction safety and health regulations can constrain or drive innovations. Safety and environmental factors can apply pressures for firms to adopt innovations or upgrade technology (Manseau and Shields 2005). The use of safety and health information dissemination and the enforcement of regulations is an effective way to increase dust-control innovation adoption among drywall companies as well as other innovations in the construction industry that increase worker safety and health. The use of regulations creates an administrative innovation decision where the decision is made by those with authority and takes away the optional innovation decision of the individual (Rogers 2003).

Another important aspect of the social system element of diffusion of innovation that can be used to help in the adoption is the use of technology champions to influence other individuals' attitudes towards adoption. Opinion leaders and change agents often referred to as technology champions (Chakrabarti 1974; Rogers 2003; Howell et al. 2005; Thompson 2006). Interventions have often used champions to provide education, champion a product, or to give support for the innovation. Reviews of interventions using champions have been found to be moderately successful

(Thompson 2006). The use of champions could be beneficial in the diffusion of dust-control technology usage by using persuasive people to increase the recognition of the innovation and share experiences. Champions provide a transfer of knowledge at an interpersonal level that plays an important part in adoption (Koebel 2008)

Technology Champions

Frequently, the term “technology, or innovation, champion” is used to label an individual who is a leader in the innovation process (Nam and Tatum 1997). There are many terms in diffusion research for an individual who acts as a champion, champions are also called opinion leaders, facilitators, linkage agents or change agents (Rogers 2003; Thompson 2006). Research has found that about 70% of construction firms have technology champions who keep others in the company aware of new products and processes. The role of champions varies between small and large firms (Koebel 2008). Champions are individuals who influence innovation in their organizations or areas of influence (Lin 1975). The role of a technology champion is to drive innovation and be able to absorb the risk of adopting innovations. A technology champion can be delegated only if the person has slack resources and enough power to implement innovations (Ling 2003).

Decisions in organizations are typically made by people of influence and the people with the most power and resources (Mitropoulos and Tatum 1999). Champions need to have past experience and resources as in time or money (Nam and Tatum 1997). Champions act as gatekeepers of knowledge who help transfer knowledge and diffuse innovations to others (Lin 1975). Champions aren’t usually assigned and can be formal leaders with titles and positions or informal leaders who others look to for information (Howell and Higgins 1990). Technology champions feel that using interpersonal relationships is a key to influencing innovation and understand that diffusion is a social process (Thompson 2006). Studies of product innovation success have shown that champions are influential in overcoming barriers to adoption within organizations. Champions who promote innovation can influence the organization to learn about new niches and to develop new processes by fostering communication within firms and stimulating managers to make decisions about innovation (Howell et al. 2005).

Based on a review of literature, many identifying factors are exhibited by technology champions. Champions are highly enthusiastic people who are willing to make special efforts and take risks to implement innovations, and are individuals who have slack resources (Nam and Tatum 1997). A champion is someone who is open to new ideas (Kramer et al. 2009). A champion needs to have a technical competence and understanding of how the innovation works, a knowledge of the company so they can identify relevant ideas, a knowledge of the market, a personal drive to push the idea ahead and get decisions made, and a champion needs to get along with different people and communicate well (Chakrabarti 1974). Champions are persistent even in the face of obstacles. They exhibit self confidence in their own ideas and are highly motivated to influence their followers (Howell and Higgins 1990). Champions are persuasive and willing to take calculated risks and adopt products as their own to promote them. Personal ownership of an idea is a critical quality of a champion (Thompson 2006). Technology champions are indispensable sponsors, protectors, and promoters of innovations who are able to negotiate and balance the opportunities of new approaches with the risks of departing from the tried and tested (Manseau

and Shields 2005). A champion is an individual who recognizes a new technology as having a significant potential, adopts the project as their own, commits to the project, and seeks to generate support from other people in the organization. A champion can arise from any level of an organization, they get resources to keep the innovation alive, they support projects when there is potential to benefit the champion's own department and are just as likely to promote innovation that are failures as they are to promote successful innovations.

Identifying a champion can be difficult but similar qualities exist in the various definitions of champions. People who are enthusiastic, committed people who are willing to take risks to implement innovations should be sought out as champions. A person may view themselves as a champion but a good way to identify a champion is through peers and senior managers (Howell et al. 2005; Thompson 2006). These qualities can be used as good indicators to identify existing champions for new technologies in the drywall finishing industry as well as promoting new champions in the intervention process.

In terms of firm owners acting as champions for safety innovations, there is a chance that the champion qualities they exhibited for tool technology could falsely identify them as a champion for a safety technology innovation. Management commitment is a strong indicator of the success of any safety intervention. If manager is not a true champion for a safety innovation, then the likelihood of the intervention having an impact on worker safety is diminished because workers can see that safety is not important to the management's goals (Marsh et al. 1998). There is a natural tendency for a champion to want to select out the desirable parts of an innovation to adopt and to reject the rest. This is often caused by a lack of efficacy of certain elements of an innovation, personal preferences of champions or strong organizational norms (Bresnen 2001). An unbalanced pursuit of purpose shows how in business situations driven by profit and production, destructive behavior can actually be incentivized. Decision making of champions can be motivated by market approval, government regulations, and safety threats that are ethically inadequate since some organizations never take the time to look at the overall purposes of their chosen practices (Goodpaster 2000). The problem with falsely identifying a innovation champion for a safety innovation is that the champion might champion the wrong behavior and the intervention may lose its original meaning and the impact might be lessened (Bresnen 2001).

Diffusion of Innovation Interventions

The matrix below provides a sample of interventions that have used the Diffusion of Innovations Model and outlines the pros and cons of the model strategies.

Table 2. Diffusion of Innovation Intervention Summary

Intervention Description	Constructs examined	Pros	Cons
Introducing Hydraulic Drop Down Aluminum	What are the barriers to adopting ergonomic	This intervention enhanced triability by providing the	The influence of technology champions

Ladder Racks to Mechanical Contractors to Prevent Musculoskeletal Disorders (Kramer et al. 2009).	innovations, Relative advantage, Complexity, the characteristics of adopting companies	contractors with the ladder racks overcoming a barrier to adoption. Technology champion contractors were sought out through other contractors and manufacturers. Educational and hands-on training was given. Compatability was addressed since it automated the same function workers already performed.	is difficult to measure. The intervention was given to few companies limiting its effectiveness
The Intention of Utility Companies to Adopt Energy Conservation Interventions (Vollink 2002)	Relative advantage, compatability, complexity, triability, adoption readiness (intention to adopt)	The intervention looked at multiple variables and showed that not all innovation characteristics need to be addressed at the same time to influence intent to adopt. A control group was used. The innovation was new and had not been implemented among participants. Decision makers were used that had the ability to implement the innovation. The innovation was evaluated and found to be cost effective if implemented	Triability was difficult to measure since this was only an intervention that addressed the intentions to use. Observability was not measured because the observability of innovation results was not relevant at the utility company level but only at the end user level. The intervention only measured intentions to adopt.
STOP AIDS intervention to promote safe sex practices among gay men in San Francisco. 7000 individuals were trained (Rogers 2004)	Opinion Leaders, relative advantage, communication	Small groups were formed with opinion leaders providing education to participants. Advantages of safe sex were related and commitment was gained for accepting the healthy behavior and participants committed to spread the information	The intervention focused mainly on intentions to adopt behavior. Measurements of effectiveness are difficult to relate to the Diffusion of Innovation Model

A review of multiple interventions that have used the Diffusion of Innovation Model as a guide for enhancing the adoption of innovations has provided insight into the direction that was taken to create intervention designs for the DUSTI project. The literature review found that there are advantages and disadvantages of using the DOI model in interventions.

The literature suggests some advantages of using the Diffusion of Innovation Model to influence adoption of innovations. The DOI model stresses the importance of different customer tendencies. The model focuses on convincing the innovators and early adopters first to increase the diffusion success (Gerrits 2005). The DOI model is generalized and can be used in many fields to increase innovation adoption with useful results. The model displays regularities across a range of various fields of studies (Rogers 2004). The model uses social networks to spread information and increase innovation adoption. Various elements are used to enhance the likelihood of adoption. Increasing perceived relative advantage of innovations, relating the compatability of the innovation with the current product or process, allowing potential adopters to try the product on a limited basis or allowing them to observe others using the innovation and

decreasing the perceived complexity can all reduce perceived barriers and increase adoption readiness (Rogers 2003).

The literature also suggests some disadvantages of using the DOI Model to influence adoption of innovations. Adopters often fall into different stages of adoption. Someone who can be seen as an innovator for one type of innovation could be viewed as a laggard for another type of intervention. A person might be an adopter for an innovation that increases productivity but a laggard for an innovation that increases safety. The DOI model is not predictive. It does not predict how well an innovation will diffuse before it has gone through its adoption curve (Gerrits 2005). Regulatory bodies might inhibit diffusion of innovations. An example of this is building codes that inhibit the use of new innovations (Oster 1977). Customers adapt innovations to their own needs and uses, which may not always correlate with the intended use of the innovation. An example relating to these interventions is the misuse of dust-control sanders by modifying the sander to be more productive while taking out the safety feature (Gerrits 2005). The decision to adopt varies according to the ability and freedom of the potential users. Some decisions can be made by an individual while other decisions are made on behalf of the individual (Koebel 1999). Outside influences on the DOI process including existing conditions, characteristics of the innovation, and communication channels can have a negative effect on the innovation process (Dooley 1999). An adopter's uncertainty about an innovation can lead them to copy the adoption practices of those around them which could lead to multiple adopters adopting inefficient innovations (Abrahamson 1991).

Diffusion of Innovation Summary

The Diffusion of Innovation Model has been used for decades to explain adoption of innovation in agriculture, construction, technology, health care banking and various other fields as a literature review by Rogers found more than 5,000 studies relating the innovation-diffusion have been conducted over the last 50 years (Hannan and McDowell 1984; Abrahamson 1991; Blackley and Shepard 1996; Oldenburg 1999; Rogers 2003, 2004; Koebel 2008). Using the four elements of the diffusion model, the innovation, communication, time and social systems as a guide can influence the adoption of new innovations in construction and particularly the use of dust-control technologies used in drywall sanding operations. The elements discussed herein were considered and were incorporated into the design of the interventions for drywall workers and firm owners to increase the diffusion of dust-control innovations and could be used to design other interventions to increase diffusion of innovation in the construction industry. The diffusion of innovation model concepts were used in conjunction with the Health Belief Model and Technology Acceptance Model.

The Health Belief Model

The Health Belief Model (HBM) was developed to explain the decision processes related to actions people take to prevent injury or illness (Rosenstock 1960). For decades the HBM has been one of the most widely used theoretical constructs used in studying health behaviors. It has

been used to explain both adoption and adherence of health behaviors and the continued following of health behaviors (Young-Corbett 2007). This model focuses on perceptions, beliefs and other personal characteristics that influence whether a person feels at risk for a certain health problem and whether they position themselves to change certain health behaviors, health practices and/or to utilize health care services (Lux 1994). Individuals who value the perceived benefits of behavioral changes will attempt to change as long as they believe their current behavior poses a threat to their lifestyle and if they feel they are capable of adopting the new behavior (Rosenstock 1988).

The main theoretical constructs that make up the HBM are: perceived susceptibility, perceived severity, perceived barriers, and perceived benefits (Rosenstock 1960; Rosenstock 1988; Elder 1999). These constructs are the major determining factors that cause people to adopt or continue practices that are meant to protect a person's safety and health. The first is the degree to which a person feels he or she is susceptible to a certain health problem or disease. The second is the severity the person believes that contracting the disease or health problem would have serious consequences to them. The third is perceived barriers to adopting a particular health practice. The fourth factor is the perceived benefits of a health action (Rosenstock 1960). Perceived threats and perceived benefits are strong motivators for a person's health practices. Perceived threat refers to a person's belief about the seriousness of a disease and his/her susceptibility to that disease. Perceived benefits refer to the amount an individual views health behaviors as being beneficial and effective (Wong and Tang 2005). Perceived susceptibility and perceived severity have been found to motivate people to act while any perceived barriers potentially stand in the way of realizing any perceived benefits. People often weigh their decisions based on the relation of barriers and benefits to adopting health behaviors. Some of the factors that are commonly weighed are cost, convenience, pain and embarrassment (Lux 1994). An adapted graphical model depicting the HBM is shown in Figure 3.

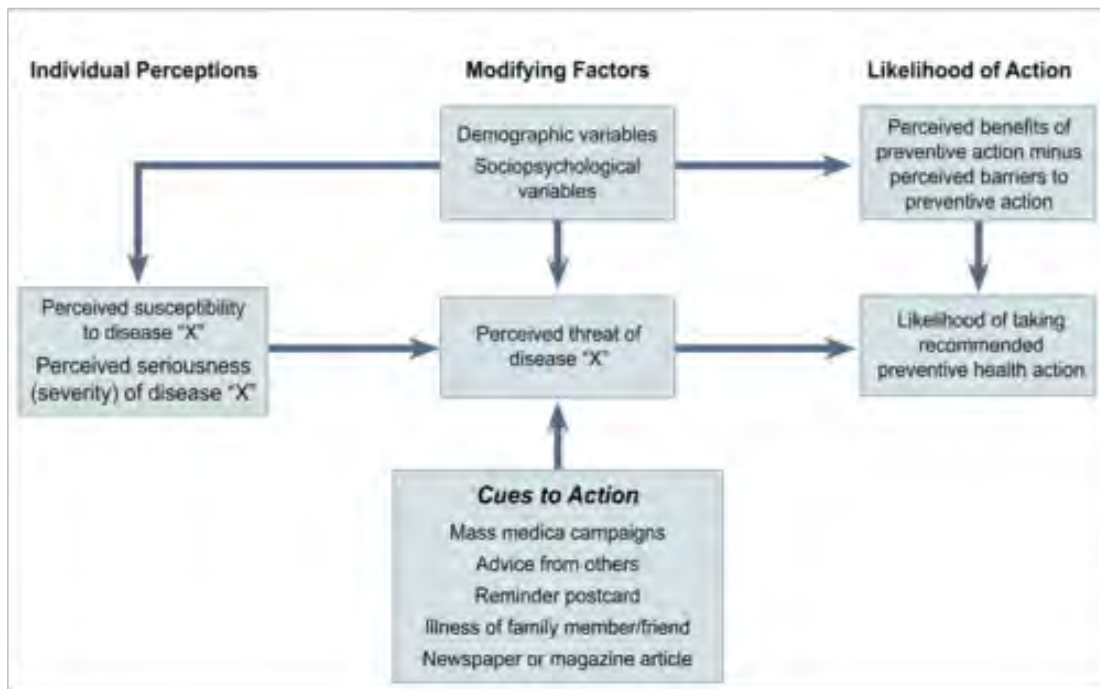


Figure 3. The Health Belief Model (Adapted from Rosenstock, 1960)

Additions to the HBM, found in the literature review, have been made to the Rosenstock version of the HBM that have been found to influence people's perceptions. In a review of HBM literature, Young-Corbett (2007) found many additions to the original HBM that have guided HBM intervention research. Demographic variables such as age, gender, ethnicity and occupation as well as socio-psychological variables such as socio-economic status and personality should be considered in HBM studies. Perceived efficacy variables such as an individual's self-assessment of his/her ability to adopt the desired behavior should be considered. Cues to action, which act as external influences promoting desired behavior, have been found to influence HBM studies. Health motivation, whether an individual is driven to adhere to a given health goal should also be considered. The perception of the risk one encounters by not undertaking the health promoting behavior should be examined by looking at perceived threats to health. These variables and influences have served to strengthen the effectiveness of HBM studies over time. The HBM constructs including modifying factors are summarized in Table 3.

Table 3. Health Belief Model Constructs

Health Belief Model Constructs
HBM Constructs: (Becker et al. 1977)
Health Knowledge (an awareness of the health risk)
Perceived Susceptibility (an individual's perception of their risk of experiencing negative health effects)
Perceived Severity (an individual's perception of the seriousness of a health risk)
Perceived Barriers (an individual's perception of factors that would discourage adoption)
Perceived Benefits (an individual's perception of the positive factors that would result from adopting a health behavior)
Self-Efficacy (an individual's perceived or actual ability to successfully adopt a health behavior)
Cues to Action (external influences that act as motivation to adopt appropriate behavior)
Modifying Factors (Elder 1999)
Demographic variables-such as age, gender, occupation
Socio-psychological variables- such as social economic status and individual personality
Health Motivation- whether a person is driven to adopt a health practice to achieve a goal

The original constructs of the HBM aim to increase health knowledge of intervention participants. The important additions that have been used in previous health interventions that were used to in addition to the aim of increasing health knowledge to create these interventions include, cues to action and self-efficacy.

Cues to Action

One important motivator that could cause a person to adopt a health behavior is a stimulus known as a “cue to action”. A cue to action serves as a trigger to the person to adhere to the appropriate behavior (Elder 1999). Cues to action could be any activity, media message, policy or trigger that catches the attention of a person and makes them dwell, however briefly, on the negative aspects of their behavior or acts as a reminder of the benefits of positive behaviors (Conrad et al. 1996). Individuals must recognize there is a problem before they are likely to change (Lux 1994). Cues to action are the most effective when introduced to their social networks including peers, family members and work associates. The HBM has found that knowledge of health risks alone doesn't motivate action. Cues to action serve as a good

motivator for people to reinforce the threats or benefits of safe work practices (Wong and Tang 2005). Cues to action can influence whether a person will be motivated to make behavioral changes. Cues to action can come in many forms such as internal cues such as symptoms or bodily states, or external cues such as health communications from others, advice from others, illnesses in other family members or co-workers or items such as a sticker on a calendar (Becker et al. 1977; Elder 1999).

Self-Efficacy

Self-efficacy refers to a person's beliefs in their own ability to perform certain behaviors (Wong and Tang 2005). Self-efficacy plays an important part in the HBM due to the user needing to feel comfortable that they are able to perform actions and protect themselves from health risks while realizing the desired health benefits (Rosenstock 1988). A certain set of beliefs including one's ability to properly control the risk is required before any action to protect one's health is taken (Rosenstock 1960). A person needs to have a certain level of trust in him or herself and also a level of trust in the existing environment and the control to be adopted (Lux 1994). Self-efficacy empowers a person to make correct choices allows them to gain control over personal, social, and administrative forces in order to take action to achieve the desired health behavior (Israel 1994). Any given behavior change is most likely to occur if the person has a desire to perform the behavior and if they have the necessary skills to perform the required behavior and there is no environmental restraints that prohibit them from performing the required behavior (Fishbein 2003).

Where actions are required to prevent health risks and maintain health, self-efficacy enhancement may be required (Rosenstock 1988). Skill training may be required to help people enhance self-efficacy before adopting a certain behavior. Performance accomplishments where the person has the ability to successfully try the skill or behavior and master the skill has been found to be the most effective method of obtaining self-efficacy (Rosenstock 1988). Vicarious experiences, that can be gained through observing others successfully or unsuccessfully practicing the skill or behavior, are another effective way to enhance self-efficacy and is the way through which much of a person's learning is gained in their life. Verbal persuasion is also used in health education while it provides a lower level of self-efficacy than performance accomplishments or vicarious experiences gained by watching others (Rosenstock 1988).

Interventions Using the HBM

In conducting a review of literature, many previous interventions have been designed and implemented using the HBM with the constructs of the HBM used as design guides and measurements for determining the effectiveness of interventions designed to increase certain health behaviors. A review of several HBM interventions is outlined using the type of intervention, the HBM constructs used, the target population of the interventions, the health behavior in question and the effectiveness of the intervention strategy. Those who design behavioral health change interventions are challenged with a number of decisions during the design process. Decisions need to be made on the messages for the intervention, the goals and desired outcomes, the target populations, and the strategies that need to be implemented (Fishbein 2003). The following interventions differ in many of the aspects of design,

implementation, and the health behaviors and actions they are aiming to change but the use of principles of the HBM are commonly used to guide the design. Interventions types are can be classified as “didactic” meaning sessions defined as primarily lectures or presentations with little interaction or discussion, “interactive” meaning techniques using participation, hands-on training, discussion groups or problem solving techniques, or “mixed” meaning using a combination of didactic and interactive methods (Davis 1999). Examinations of five interventions that are representative of examples of interventions using the HBM have been summarized in Table 4.

Table 4. Summary of Health Belief Model Intervention Examples

Intervention Type	HBM Constructs	Target Population	Health behavior of interest	Effectiveness of Intervention Strategy
Mother's health motives	Health knowledge, perceived susceptibility, perceived severity, perceived benefits, perceived barriers	Mothers of obese Children	Dietary adherence and health beliefs	High fear intervention showed results of higher weight loss
Cancer, Tuberculosis and Heart Disease	Health Knowledge, perceived susceptibility, perceived severity, self-efficacy of taking action, perceived benefits	General Population	People's knowledge and health beliefs about cancer, tuberculosis and heart disease	Educational materials increased perceived susceptibility, self-efficacy, and perceived benefits of accepting health behaviors. Doctor visits, exercise, and diet changes were reported following intervention
Lead Safety among Painting Contractors	Health Knowledge, Self-efficacy, perceived benefits of healthy behaviors	Painting Contractors and their employees	Implementation of safe practices when working with and around lead paint including: Washing hands before eating, wearing respiratory protection, performing daily face seal checks on equipment, wearing work clothes home, eating and drinking in work areas.	Improvements in employee safe practice behaviors were shown to improve post intervention. Not all areas of interest met the target improvement rates that the intervention had set as goals.
Tailored dietary messages	Self-efficacy, Perceived susceptibility	Adult patients visiting family practice medical offices	Change in diet to reduce fat levels	The tailored message showed a significant decrease in total fat as compared with the non-tailored group showing the effectiveness of a tailored message to individuals readiness to change their behaviors
Sexually transmitted disease prevention	Health knowledge, perceived susceptibility, perception of benefits, Perceived Ease of Use, self efficacy	Minority Women	Safe Sex practices	The effectiveness of the intervention was measured by the decreased rates of sexually transmitted diseases among high-risk minority women. There was a significant decrease in the amount of women in the intervention attributed to the use of behavior change theories and promotion of self-efficacy.

HBM interventions address a variety of health behaviors and issues. Other intervention examples not discussed in detail but discovered through the literature review include interventions to reduce smoking, interventions to increase breast cancer screening, increased nutrition at worksites, increase in colorectal cancer screenings, increased diabetes awareness and prevention, increased vaccination participation and various other health related concerns (Bastani 1995; Conrad et al. 1996; Vernon 1997; Aoun et al. 2002; Abood 2003; Dempsey 2006). Worksite health promotion programs have been used to protect employee health and to encourage employees to practice safe behaviors (Conrad et al. 1996; Rychetnik 2002). Health and safety interventions require a variety of channels to deliver messages, products and services to target populations. Consideration needs to be given to what channels the target audience will come into contact with on a regular basis as well as attention to the nature of the message that will be delivered (Craig Lefebvre 1988).

The HBM has been used as a model for behavioral interventions for decades and has shown to be applicable to various situations. Worksites remain an important domain for reaching adult populations with health information. Results from worksite health promotion activities have yielded promising yet modest health behavioral changes while evidence suggests that employees who participate in workplace health promotion interventions achieve positive health outcomes (Linnan 2001). Helping workers to become aware of the risks they are exposed to by increasing health knowledge, perceived susceptibility, perceived severity and helping them to break down any perceived barriers by teaching self-efficacy and allowing them to realize the benefits of healthy behaviors can easily be adapted to work site situations and hazards. Workplace interventions can adapt the HBM by using the work environment to teach self-efficacy and items and people in the workplace serve as cues-to-action triggers to enforce the objectives of the intervention (Conrad et al. 1996)

The literature suggests some advantages of using the HBM to influence health related behaviors. The HBM is a widely used model that has been shown to enhance the adoption of healthy behaviors and practices in many fields. The HBM has been used successfully to increase health knowledge about the risks of certain behaviors which has shown to reflect on the constructs of perceived severity and perceived susceptibility, which can predict compliance with health behaviors (Becker et al. 1977). The HBM can increase self-efficacy, which allows for participants to gain confidence to overcome barriers that might exist. Performance accomplishments have been found to be influential in enhancing efficacy and reducing the perceived difficulty of adopting healthy behaviors (Rosenstock 1988). The HBM utilizes various channels of communication to trigger participants to practice healthy behaviors. Cues to action provide a trigger or stimulus for the behavior. Cues can come from many forms of communication including internal cues such as symptoms or external cues such as family members, peers, or media such as television, radio or printed channels (Elder 1999)

The literature suggests there are also disadvantages to using the HBM to influence health related behaviors. The beliefs and actions of people are subject to change over time and depending on their situation and interactions with others (Rosenstock 1960; Finfgeld 2003). Direct attempts to change a person's beliefs are not always effective and efforts should be focused on removing environmental factors that could be seen as barriers to change (Strecher and Rosenstock 1997). The constructs of the HBM have often been thought of as independent

components rather than directly or indirectly interdependent on each other and have often been misused in HBM studies (Streicher et al. 1997; Finfgeld 2003). Most HBM research has incorporated only selected components of the model that results in the model as a whole failing to be tested (Janz 1984). The HBM is limited in that factors other than health beliefs also influence health behavioral practices. These factors may include cultural factors, previous experiences, socioeconomic status and external pressures from organizations or peer groups (Elder 1999).

Technology Acceptance

The Technology Acceptance Model (TAM) was developed by Davis (1989) to explain the factors that influence the decisions to accept or use new technology (Venkatesh 2000b). The TAM was originally designed to understand and predict user intentions to accept new computer technologies but has been used to understand technology acceptance in various fields of study including medical technology, information systems, and information technology (Chau 1996; Hu 1999; Venkatesh 2000c; Brown 2002; Yi et al. 2006). The TAM has been used to show that perspective adopter's behavioral intentions to use a technology correlate to the actual usage of the technology (Chau 1996). If potential users do not fully accept the new technology they can obstruct the new system and cause it to be underutilized (Brown 2002). The TAM is comprised of two main constructs which are perceived usefulness (PU) and perceived ease of use (PEOU) (Davis 1989). PU is defined as the degree a person believes that using the a new technology will increase their effectiveness or performance while PEOU is defined by the potential adopter's view of how much effort will be required to adopt the new technology (Davis 1989; Venkatesh 2000b). These two constructs of the TAM have been shown to be strong determinants of predicting adopter's intentions to accept technology (Venkatesh 2000b).

PU has been found to have a strong influence on people's perceptions of new technology (Chau 1996). Davis (1989) further described perceived usefulness by showing six ways potential adopters judge the usefulness of a technology which include: (1) does the technology allow the adopter to do their job more quickly? (2) Does using the technology improve the user's job performance? (3) Does using the technology increase productivity? (4) Does using the technology increase the effectiveness of the user's job? (5) Does using the technology make it easier for the user to do their job? (6) Does the user find the technology useful? PU can have short term implications to a user such as improving job performance or it can also have long term implications to a user such as improving the user's status in the company over time or improving the user's health (Chau 1996). People form usefulness judgments by comparing what the new technology capable of doing and what they need to get done to fulfill the requirements of their job. There are similarities between PU construct of the TAM and the relative advantage construct in Rogers diffusion of innovation model (Chau 1996; Rogers 2003). A focus on PU and relative advantage will help in the design of effective interventions that promote acceptance of new technology (Venkatesh 2000b)

PEOU can also have a strong influence on potentially increasing acceptance of new technology. The perception that a technology is easy to use will have a direct effect on its acceptance since technology viewed as being easy to use is more likely to be accepted (Davis 1989). PEOU also has an indirect effect on acceptance in its correlation to PU. If a technology is viewed as easy to

use, then the perceived level of usefulness has also been found to increase (Hu 1999; Brown 2002). PEOU has been shown to have a smaller but still significant effect on user intentions to accept technology. This effect decreases over time due to the user gaining self-efficacy with the system with increased usage (Chau 1996). PEOU has been found similar to the construct of complexity from the diffusion of innovation model in showing that the adoption of technology is determined by its perceived attributes (Yi et al. 2006). The construct of self-efficacy has also been compared to ease of use in that a persons' perception of efficacy with a technology can influence their view on the ease of use the technology offers (Venkatesh 2000c; Yi et al. 2006). The influence of PEOU is greater in organizational settings where adoption is mandatory while in voluntary settings PU is the stronger determinant of behavior intention to use technology (Brown 2002).

A matrix is given in (Table 5) evaluating a sample of interventions that have used the Diffusion of Innovations Model in which pros and cons of the Model strategies are highlighted.

Table 5. Technology Acceptance Model Interventions

Intervention Description	Constructs Examined	Pros	Cons
Introduction of a new computer management system for floor supervisors in manufacturing firms (Venkatesh 2000b).	Perceived Usefulness, Perceived Ease of Use, behavioral intention to use	The decision to use the technology was voluntary. The subjects received training including one day of on-the-job training with the technology. Validated measurement instruments were used as effective measurement tools. It only measured intentions to use and not self-reported usage that avoided the common method variance limitation of measuring both on a single questionnaire	Several of the constructs were measured with only two items. The sample sizes were small and the intervention was an observational design and nothing was done in effort to enhance user intentions to accept the technology. Intentions were self-reported.
An intervention to increase physician's decisions to accept telemedicine technology in health care (Hu 1999).	Perceived Usefulness, Perceived Ease of Use, behavioral intention to use	Most measurement items were obtained directly from literature. Validity and reliability steps were taken. Results showed that the PU construct had an affect on behavioral intention to use	No training was provided and no efforts were made to enhance user intentions to use. The participation in the study was voluntary and may have only included physicians who are interested in or had used the technology.
An intervention introducing a new interactive online help desk system (Venkatesh 2000a).	Perceived Usefulness, Perceived Ease of Use, behavioral intention to use, perceived voluntariness	Measured user reactions to the new system. User reactions were tracked over time as users became more experienced using the system. Validated instruments from prior research were used in measuring the constructs. The acceptance of the technology was voluntary. Computer self-efficacy scores acted as a control. Training was conducted by a group of 3 individuals with no knowledge of the research.	The training did not focus on increasing the intentions of users to accept the technology but rather focused on teaching self-efficacy in effort to enhance perceived ease of use through the gaining of experience using the technology.

Over the past 20 years the TAM has become a well-established model for predicting user acceptance (Venkatesh 2000b). A review of multiple interventions that have used the Technology Acceptance Model as a guide for enhancing the adoption of innovations has provided insight into the direction that was taken to create the intervention designs for the DUSTI project. A general summary of the pros and cons of the Technology Acceptance Model interventions studied are listed below.

The literature suggests there are advantages to using the TAM to influence adoption of innovations. The TAM construct of perceived usefulness has shown to be a strong determinant of usage intentions (Venkatesh 2000b). The TAM has been found to be influential in determining the acceptance of technology and has strong theoretical basis and empirical support (Hu 1999). TAM has been used generally to predict intentions to adopt technology in a wide variety of fields and has a large inventory of validated measurements that make it operationally appealing (Hu 1999). Training interventions using the TAM can positively influence PEOU (Venkatesh 2002).

The literature also suggests there are disadvantages to using the TAM to influence the adoption of innovations. The TAM fails to incorporate social influences and voluntariness. Social influences affect acceptance of technology in that if a person feels favorable or unfavorable towards a technology, they still may choose to adopt or not adopt depending on if they feel someone they consider important feels they should. Voluntariness affects acceptance due to the adopter's perception that acceptance is non-mandatory. If a user feels the usage of technology is mandatory this may affect their intentions to use. Compliance-based interventions mandating the use of technology have less effect than the use of social influences to affect an adopter's perception of usefulness (Venkatesh 2000b). The effect of perceived ease of use diminishes over time and becomes insignificant in predicting intention to use (Hu 1999). The TAM evaluates behavioral intentions to use and not actual usage of technology (Chau 1996). The TAM can yield different results when technology acceptance is mandatory instead of voluntary (Brown 2002). The TAM assumes that there are no barriers preventing an individual from adopting if the user chooses to adopt. Perceived user resources should be included in the model (Mathieson 2001).

Trust in Technology

In order for changes in work procedures and practices in relation to technology acceptance to take place, trust must be a fundamental part of the organizational culture if the change is to be sustainable and adopted effectively (Podsakoff et al. 1996). Trust is related to a person's dispositions, decisions, behaviors and social networks. Trust is not a behavior or a choice, but rather a condition that can cause results that leads to action (Rousseau 1998). Trust has a direct influence on a behavioral intentions to use a technology and has a positive effect on the PU and PEOU constructs of the TAM (Wu and Chen 2005). Trust in technology is defined as an individual's willingness to be vulnerable to a technology based on that individual's expectation that the technology will exhibit the elements of predictability, reliability and utility (Lippert 2005). Trust in technology research has been conducted in various fields including ecommerce, online

marketplaces, information systems, medical technology and food science (Eiser 2002; Misiolek 2002; Yee 2005; Li et al. 2008; Montague et al. 2009). In a study on trust in medical technology conducted by Montague (2009), participants described trust in technology in three different categories. These categories include:

1. Actions that a person performs when they trust a technology. Examples include: using a technology, consenting to use, purchasing, and trusting it with important information or safety.
2. Feelings about the technology. Examples include: having faith, believing in the technology, and feeling comfortable.
3. Actions that the technology performs leads to trust or distrust. Examples include: being accurate, being reliable, being understandable, being easy to use and matching assumptions (Montague et al. 2009).

Trust in Technology includes two constructs, perceived risks and perceived benefits which have an indirect impact on the acceptance of technology (Siegrist 2000). Potential users are less likely to experiment with a new technology if they perceive it as being too risky (Li et al. 2008). Trust in technology, which can lead to acceptance of new technology, is based on the perception of risk which is influenced by the information potential users receive about the technology (Eiser 2002). Recent research indicates that increasing trust helps potential users overcome perceptions of risk and uncertainty in the use of new technology (Li et al. 2008). Trust in technology is built when the perceived benefits can be seen and the tangible results of the technology are apparent to users (Yi et al. 2006).

Predictability, reliability and utility are important elements of building trust in technology through their ability to address the constructs of perceived risk and perceived benefits. Predictability refers to the expectation that the technology will perform the desired function in a manner that is expected by the users (Lippert 2005). The users of a technology determine predictability by seeing the technology do what it is designed to do and as the technology exhibits the desired predictability then trust in the technology will build over time (Lee and Moray 1992). Reliability refers to user's confidence that the technology will perform the desired function in situations that involve some degree of risk where if the technology does not perform, the user is placed in a position of vulnerability (Lippert 2005). Most definitions of trust include multidimensional aspects and tend to include reliability as a factor of trust (Dzindolet et al. 2003). Attitudes towards new innovations are often shaped by the reliability and accuracy of the innovation (Parasuraman and Riley 1997). Utility is the perceived usefulness of a technology. If a technology is perceived as useful then trust in that technology is increased (Lippert 2005). If a user considers a technology useful, and perceive that it will improve their performance, then they are more likely to trust in that technology (Johnson 2007).

The level of risk in adopting new technology affects trust and could be a factor in determining whether to use or not use new technologies (Parasuraman and Riley 1997). The design of new innovations should allow the operators to trust in the innovation that the desired quality and function will be achieved and should give the operator self-confidence in their ability to properly use the tool and receive the benefits (Lee and Moray 1994). An important aspect of trust in technology is the user understanding how the technology works. The more someone understands how something works, the more likely they are to put their trust in it (Dzindolet et al. 2003). Better operator knowledge of how a technology works will result in more appropriate use of technology (Parasuraman and Riley 1997).

The decision to perform a job manually versus to use technology to perform the task depends on the operator's level of trust in the piece of equipment. If an operator lacks trust in a piece of equipment then barriers are formed which limit the potential for increased adoption and use of the technology (Lee and Moray 1994). To promote the appropriate use of technology, operators of new technology should be made aware of any biases they may bring to the use of the technology. Human operators are likely to dislike or even mistrust the innovation. As experience is gained, trust improves as the technology demonstrates reliability and accuracy (Parasuraman and Riley 1997). Trust can positively influence a user's decision to adopt by providing information, credibility and reliability (Yee 2005).

Technology Adoption

Once trust is gained in a technology and the user has exhibited an intention to use the technology, the user looks for accurate and reliable information to remove any uncertainty before and after adoption (Yee 2005). The TAM of Davis (1989) is used to analyze why users choose to accept or reject new technologies. Technology adoption is the actual usage of the new technology (Ammenwerth 2006). The benefits from technology are dependent on the level the technology is utilized. Technology adoption decisions require information with the most significant factors for adoption include: the benefits of implementing the technology, organizational culture, availability of the technology and self-efficacy in using the technology (Fink 1998). Once the potential adopter gathers and evaluates the information and decides to adopt the new technology, the adoption can happen all at once or incrementally (Mitropoulos and Tatum 1999). Adoption of new technology includes three critical decisions which are: whether or not to adopt the new technology, the degree of which the new technology will be implemented and utilized, and the speed which the new technology will replace the old technology (Astebro 2004).

The decision to adopt can be difficult due to possible uncertainties of the new technologies and the view that old investments in previous technologies will have been wasted (Srinivasan 2002). Knowledge about the technology and the opinion of others are often considered in the decision to adopt or reject a new technology (Fink 1998). Decisions to adopt are based on maximizing benefits and reducing risks that could help a person or organization to gain a competitive advantage (Mitropoulos and Tatum 1999).

The investment of time can be a determining factor of decisions to adopt. The amount of workload a potential adopter has might inhibit the decision to adopt due to not wanting to invest the time into learning how to use a new technology when the old one gets the job done. The risk of adopting the new technology or the risks that are present by not using the technology weigh into the decision of whether or not to adopt (Parasuraman and Riley 1997). If a potential adopter is able to personally experience the benefits of the new technology or are consistently satisfied with the technology and can see that potential PU and PEOU barriers have been overcome, the decision to adopt is strengthened (Lippert 2005).

The degree or depth of which new technologies will be implemented and utilized is a critical decision for potential adopters of new technologies. Depth of adoption doesn't necessarily mean the amount of technology purchased, but rather the degree to which the technology is being utilized to receive the desired benefits of the technology (Astebro 2004). Technology adoption at the organizational level does not always mean greater depth of adoption since all users in the organization may not always fully adopt the new technology or use it correctly (Misiolek 2002). Adoption of new technology depends on the attributes of the users and the technology itself. The user's attributes of self-efficacy (their perceived capacity to interact with the technology), motivation to use the technology and attitude towards the technology can possibly affect the depth of adoption (Walker 2002). The usability, performance and function of the technology also possibly affect the depth of adoption (Ammenwerth 2006). The cost of new technology can also increase or decrease the depth of adoption of the technology (Srinivasan 2002).

The speed that a technology can be implemented is another decision in the technology adoption process (Astebro 2004). Adoption of new technologies usually occurs in phases in effort to limit the risk of adopters (Fink 1998). Institutional pressures can often drive the speed of adoption in the form of stakeholders and competition. Stakeholder pressures can come from internal stakeholders such as management or employees or external stakeholders such as customers, investors, insurance companies, the general public, media, or government interactions. Competitive pressures force firms to adopt technologies in order to gain a competitive advantage or simply to continue to compete with other organizations (Srinivasan 2002).

Trust in Automation

When new automated technology is introduced to the workplace, instant acceptance is generally limited to a few cases. Many users may dislike the new technology and may be hesitant to trust the technology (Parasuraman and Riley 1997). The decision to perform a job manually or using automation depends on the operator's level of trust in the technology (Lee and Moray 1992). The more a user understands how an automated technology works, the more likely the user will trust in the technology (Dzindolet et al. 2003). Trust in automation is a principal factor for acceptance and usage of the technology (Madhavan et al. 2006). Trust in automation is an expectation that the automated technology will function in a consistent manner in the future in a manner that is predictable and reliable (Lippert 2005).

Automation is used when the operator's trust in the technology exceeds the operator's self confidence in performing the task manually and not used when the opposite is true (Lee and Moray 1994). Reliability, accuracy and availability are required for user trust in automation (Riegelsberger et al. 2005). If the automation is perceived to have errors, the level of trust in the automation is decreased and the level of self-confidence in manual operations is increased due to the attitudes toward the automation being formed by the reliability and accuracy of the automation (Parasuraman and Riley 1997; Madhavan et al. 2006). Trust in automation is important to achieve the benefits of technology. Potential problems exist when the user places too much trust too much in automation or don't trust automation enough. People become over reliant on automation when high levels of trust exist and lose out on potential benefits of the automation when levels of trust are low (Dzindolet et al. 2003). When mandatory acceptance and use of an automated system is implemented, operators who do not have trust in the automation can result to creative ways of disabling the automation and getting the job done other ways (Parasuraman and Riley 1997). Mistrust of automation can lead to failures and can undermine the potential benefits that the automation could provide. Trust in automation is dependent on the characteristics of the operator, the automation, and the way they interact (Lee and See 2004).

Trust in Organization

Many American workers are suspicious of management (Gilbert and Tang 1998). Forty-three percent of all American workers can be described as cynical and mistrusting of their organization and other employees. Organizational trust is the belief an employee has in an organization that the employer will be straightforward and follow through with commitments made. Organizational trust refers to employee faith in company leaders, goals and that the company will do what is best for the employee (Gilbert and Tang 1998). Trust is composed of predictability, dependability and faith. In the cases where employees do not trust their organization, workers tend to spend time protecting their self interests and hold back from the organization. Trust needs to begin at the top and filter down throughout the organization (Mishra and Morrissey 1990). Building organizational trust is not easily wrought from the top down in an organization. Organizational trust needs to be built by taking into account the needs, fears, and motivations of all staff levels (Davies et al. 2000). One important factor of trust in organization is communication. Without trust, resistances to change and conduct are more prevalent (Carnevale 2008).

As people generally tend to trust other people more than companies, managers can build employee trust by communicating information that is reliable and by standing by the promises the company makes and exceeding employee expectations (Rezgui 2007). Leaders who gain the trust of employees can increase employee's role clarity, attitudes, satisfaction and organizational commitment and trust. Employees who view themselves as having a high degree of ability and experience are more likely to place a higher degree of trust in the organization than those who do not view themselves as having the ability and experience in the company (Podsakoff et al. 1996).

Decreased human relations and organizational performance, low employee morale, and reduced quality of work are results of organizational mistrust (Gilbert and Tang 1998). Better communication, sharing in decision making and sharing of information with employees helps to build organizational trust (Gilbert and Tang 1998). If the culture of an organization had led to mistrust, then it may be possible to create, change and manage the culture of the company in order to change the level of organizational trust (Davies et al. 2000). The lack of trust has been found to have a more negative effect than the presence of trust is positive in its influence (Mishra and Morrissey 1990).

Overview of Trust and Acceptance of Technology

Trust in technology, trust in automation, technology acceptance and technology adoption literature reviewed revealed that each of these areas of studies are aimed toward the increased usage of technology. These constructs are often used in connection with each other and sometimes are combined to explain adoption of technology. There are similarities these four constructs share that help them to build upon each other and strengthen the depth of adoption as well as differences that make them unique areas of study in which increased focus can be placed in order to gain greater understanding of each construct. Trust is needed in each of these constructs and increased trust leads to increased adoption.

Literature suggests there are similarities between the constructs of trust in technology and trust in automation. Trust in technology is similar to trust in automation in that in order for trust to be increased, the technology or automation has to be perceived as accurate, reliable and useful (Lippert 2005; Riegelsberger et al. 2005). When a user trusts the technology that provides automation, then the automation will be utilized. Both constructs are necessary elements of acceptance and usage of technology (Lee and Moray 1992; Podsakoff et al. 1996). Having faith in, believing in and feeling comfortable with the technology are elements that also exist in both trust in technology and trust in automation (Lee and Moray 1992; Montague et al. 2009). Perceived risks must be overcome and perceived benefits of the technology must be tangible for trust to be increased in both constructs (Siegrist 2000; Riegelsberger et al. 2005). Both trust in technology and trust in automation are dependant on the user's understanding of the technology (Dzindolet et al. 2003; Yee 2005).

The literature also suggests there are differences between these two constructs. Trust in technology is a part of trust in automation. Decisions to use automation are dependant on the level of trust in the technology (Lee and Moray 1992). Trust in technology might exist, but an important factor in trust in automation that differs from trust in technology is that if the user has greater trust in their abilities than they do the technology, then the usage of the technology is not realized (Lee and Moray 1994).

Enhancing trust in technology

Trust is a subjective concept that is affected by individual and situational differences The development of trust in technology is based on user's view that the technology will

benefit the user (Wang 2005). Guidelines used in various interventions (air traffic control, medical, computers, CAD, information systems) introducing new technologies have been used for enhancing trust and include: education, user experiences, ability (skills, and competence), integrity (credibility and dependability) and reducing risk (Steinauer 1997; Eiser 2002; Yee 2005; Shea 2008). The barriers of trust enhancement include the lack information and training, fear brought on by uncertainty and resistance to changes (McBride and Morgan 2010). The guidelines with their strengths and weaknesses are discussed below including how they can be implemented into interventions for increasing trust in dust-control technology.

Educational information that is designed to enhance a user's knowledge about the technology can increase trust by removing uncertainty about the technology and is an important first step in building trust (Yee 2005; Shea 2008). Information is important for the initial formation of trust and provides a strong base for which trust in technology can be built upon. Educational information's weakness is that information alone may not build enough trust in the technology to lead to adoption. Information only provides a starting point that can help remove uncertainties. The effect of information provided by others on user trust diminishes over time and the user will form their own trust in the technology through experience (Venkatesh 2000c). Educational materials were used to inform drywall workers and employers about the dangers of drywall dust and how dust-control technologies work and the benefits of using the technology.

User experiences with a technology build trust as the user becomes more familiar with the technology, trust will be enhanced (Steinauer 1997). Experiences are used to develop the level of faith that a user places in the technology. Trust is enhanced over time by having positive experiences with the technology (McBride and Morgan 2010). The weakness of user experience as a guideline for trust enhancement is that not all users have experience using the technology and if they have bad experiences then their trust will be diminished. These interventions provided new users the opportunity to gain experience with the dust-control technology, which was aimed at increasing their level of trust in the technology. The more experience they have with the technology, the more likely they are to trust the technology (Corbitt et al. 2003).

Demonstrating ability can increase trust in a technology. As ability, which also can be defined as the skill or confidence a user has in the technology, of the user increases, their confidence using the technology will be enhanced (Shea 2008). Ability is similar to the construct of self-efficacy as outlined in the HBM. The technology must have the functionality to complete the desired task and the user must be adequately trained in the use of the technology (Ammenwerth 2006). While users may be willing to try a new technology, they may become frustrated and trust may decrease if they lack the skill and self-efficacy to reap the benefits of using the technology. Skill training is needed to help users avoid mistakes that could diminish trust. (Shea 2008). A weakness that could occur as a result of demonstrating ability is the training that the person receives needs to be reliable. Educators must not only be able to perform the skill but must be able to instruct others how to do it as well (Shea 2008). Hands-on skill training using the dust-control

technology was used in the design of these interventions, allowing the user's to gain skills and confidence using the technology the proper way.

Demonstrating integrity includes providing information about the technology that gives it credibility and reliability, and allows for the user to check the results (traceability) has been used as a trust enhancement method (Yee 2005; Shea 2008). Endorsements (from major firms, government or other respected organizations) and formal testing or certifications can be used to enhance credibility and reliability that help establish trust in technology (McBride and Morgan 2010). If a user is able to check the results of a using a technology against their expectations, trust can be enhanced (McBride and Morgan 2010). A weakness of demonstrating integrity could be that not all people value the recommendations of others the same and if they don't see perceived value, then trust will not be enhanced. These interventions used endorsements from NIOSH in the form of published reports on the effects of drywall dust and the beneficial use of dust-control technologies to help establish credibility. Results from dust-control studies conducted at Virginia Tech University (Young-Corbett, 2007) were used to show the reliability and effectiveness of dust-control technologies. Traceability was utilized by allowing the users to visibly see the lower levels of dust generated either in on-site demonstrations or web-based video-trainings depending on the intervention type.

Reducing Risk is a way to enhance trust in technology (McBride and Morgan 2010). Perceived risk influences a person's trust and ultimately their acceptance of a technology where lower levels of perceived risk lead to greater trust in technology (Eiser 2002). One way that has been used to enhance trust is to inform the potential users of the risks of using or not using a technology and also how those risks can be minimized (Johnston et al. 2003). The weakness of using risk as an enhancement of trust is that people have different perceptions of risk and are willing to accept different levels of risk. The risk of not using dust-control technologies could vary depending on the situation and user. These interventions attempted to inform the participants of the risks of not using dust-control technologies in effort to enhance trust in the technology.

Enhancing Trust Calibration

Even when trust has been formed in a technology, the benefits of using the technology will still require an educated user who understands the risks and benefits the new technology offers (Wang 2005). Maximizing trust in a technology can sometimes be a poor design goal. If too much or not enough trust is placed in a technology, potential risks arise and that could affect the level of user trust (Parasuraman and Riley 1997). A level of trust is needed that allows for trust to be calibrated properly so the user is able to gain the benefits for using the technology (McBride and Morgan 2010). Proper calibration prevents the misuse and disuse of a technology that could lead to decreased trust, errors, inefficiencies and even rejection of technology (Lee and See 2004; Fallon 2010). Methods used for calibrating trust are training and user experience (Fallon 2010; McBride and Morgan 2010).

Training that helps the operator understand the capabilities of the technology can enhance calibration of trust by allowing the operator to know when to adopt and apply the technology (Fallon 2010). Training is important in the calibration of trust but may not be adequate enough to prompt usage of technology (McBride and Morgan 2010). Information alone may not enhance the appropriate calibration of trust. The information needs to be presented in a way that the user can understand and incorporate into the experience of using the technology (Lee and See 2004). The weakness of training is that alone it may not adequately calibrate the appropriate level of trust in a technology. These interventions incorporated training on the technology and focus on calibrating the user's trust in the dust-control technology by providing and understanding of how the system works and when to use the system.

User Experience using the technology helps the operator to calibrate their trust in the technology. Experiences help the operator to determine the level of faith they can put in the technology at different times to realize the benefits of the technology. If an error occurs then the level of trust changes and must be regained (McBride and Morgan 2010). Using experiences to calibrate trust can be a weakness because if positive experiences are expected, misuse of the technology occur and if negative experiences occur it could result in disuse or abandonment of the technology (Lee and See 2004).

Enhancing Technology Adoption

The decision to adopt technology is often difficult due to uncertainties about the technology and the effect it will have and that old investments in previous technology may be viewed as lost (Srinivasan 2002). A properly calibrated trust in technology can enhance adoption of technology. Adopters are different from each other in how they view potential technologies for adoption although they can compare the experiences of others with their own experiences to form decisions whether to adopt or not (Malhotra 1999). Training is a critical component of technology adoption (Leonard 2004). Methods that interventions should focus on to increase technology adoption include training on: perceived risk and benefits, external pressures to adopt, CEO support and user participation (Fink 1998).

Perceived Risks and Benefits training gives the decision maker the support they need to overcome adoption obstacles. The positives and negatives of the technology must clearly be communicated and the purpose of the technology should be made clear so trust can be developed (Leonard 2004). Adoption of technology can be increased by showing that the technology is functional enough to complete the desired task since users who personally can see the technology as useful have a greater affinity for adoption (Malhotra 1999; Ammenwerth 2006). Training of perceived benefits should also include focusing on how the technology can maximize the benefits by creating a competitive advantage for the user and that the probability of success will be high (Mitropoulos and Tatum 1999). The weakness of focusing on the perceived risk and benefit is that people view these items differently and it doesn't take into account the ability of the user to use the technology that is a barrier to adoption. Typically researchers have focused on adoption from a perceived risk and benefit standpoint using the TAM constructs of PU and PEOU which

can overlook individual differences of users (Venkatesh 2000a). These interventions incorporated education on the risks and benefits of using dust-control technology in efforts to increase acceptance of the technology that can lead to increased adoption.

External Pressures to adopt can enhance technology adoption. External pressures that have used to enhance adoption include stakeholders such as the general public, customers, investors, insurance companies, and government regulation (Srinivasan 2002). Outside forces can serve as motivation for firms to adopt new technology. The weakness of using external pressures is that if the pressure to adopt technology doesn't lead the users to believe that the technology is trustworthy, then the decision to use the technology will not happen (Wang 2005). These interventions incorporated how external stakeholders namely customers, government regulators and insurance companies support the adoption of dust-control technology.

CEO Support plays a significant role in the adoption of technology in small firms. The management of a company needs information about the technology in order to have the motivation and courage to adopt new technology (Fink 1998). The weakness of using CEO support to enhance adoption can be that the CEO doesn't have enough information about the technology to make an informed decision or doesn't trust the technology. These interventions focused on informing the owners of small companies about dust-control technology benefits and strengths since managerial attitudes toward technology affect adoption decisions (Mitropoulos and Tatum 1999). Drywall-sanders were also given to the small firm intervention participants in effort to provide the owners a risk free trial of the technology that can enhance adoption. **User Participation** is used as a technology adoption enhancer since adoption often depends on the attributes (self-efficacy, motivation, and attitudes) of the user (Walker 2002; Ammenwerth 2006). User involvement, user training and motivation by management have been used in interventions to encourage user participation to enhance adoption of technology. The weakness of user participation is that the user must be motivated, have the required knowledge and ability to complete the required task (Ammenwerth 2006). These interventions encouraged user participation in training sessions through hands-on training with the tools to enhance self-efficacy, increase motivation and attitudes towards the use of dust-control technologies.

Health Promotion Intervention Strategies

Some of the common strategies found through the review of health promotion intervention literature using the three theoretical models will be used to create the interventions for dust-control technology usage and could enhance intentions to use dust-control technology. The most common and effective methods are educational materials, self-efficacy training and social system influences.

Educational training materials- Educational materials should be administered through short lectures and handouts that can increase awareness of the effects of drywall dust and provide information that is important to increase the health knowledge of workers and employers. Educational training will provide participants with information pertaining to

the following constructs that can influence perceptions of ease of use and usability of technology which then directly influence the intention to use new technology: Perceived Susceptibility (HBM), Perceived Severity (HBM), Perceived Risks (HBM, TAM), Relative Advantage (DOI), Reliability (DOI), Compatability (DOI) an Complexity (DOI). These materials can include information that supports the severity of the problem that might cause a fear motivation in some participants, which in turn might motivate them to improve unsafe behaviors. Using training methods known to be effective with adult audiences which include minimizing lecture time and combining them with graphics and visuals can enhance the effectiveness of construction safety interventions (Materna 2002).

Self-Efficacy Training- Teaching workers and employers how to use the engineered methods for dust control can be an important factor for breaking down any barriers that might exist for using the tool and increasing the skill of workers. This training can be done through hands-on demonstrations at the worksite enabling the participants to ask questions and gain familiarity with the tools and methods. This hands-on training incorporates the elements of all three models used in the design of the intervention by increasing self-efficacy (HBM), increasing trust by demonstrating the ease of use and perceived usefulness of the tools (TAM) and by allowing participants to overcome perceived barriers through triability and observability (DOI). Since performance accomplishments are the most effective source of efficacy, the intervention should include worker experience with the tools (Rosenstock 1988).

Social System Influences- Introducing changes into a construction social system can create ripple effects that can be difficult to anticipate (Manseau and Shields 2005). The culture of a company can play an important role in the adoption of innovations within a social system and innovations should try to be compatible with the normal behaviors that are in place. Structural barriers such as building codes, and construction safety and health regulations can constrain or drive innovations and can influence actual usage of technology. Safety and environmental factors can apply pressures for firms to change intentions to adopt innovations or upgrade technology (Manseau and Shields 2005). Another import aspect of the social system element outlined in the DOI that can be used to help increase intent to adopt is the use of technology champions to influence other individuals' attitudes towards adoption. Opinion leaders and change agents often referred to as technology champions (Chakrabarti 1974; Rogers 2003; Howell et al. 2005; Thompson 2006). Interventions have often used a champion to provide education, champion a product, or to give support for the innovation. Reviews of interventions using champions have been found to be moderately successful (Thompson 2006). The use of champions could be beneficial in the diffusion of dust-control technology usage by using persuasive people to increase the recognition of the innovation and share experiences. Champions provide a transfer of knowledge at an interpersonal level that plays an important part in adoption (Koebel 2008)

Construction Safety Interventions

The intensity of work, time pressures, frequent changes of work locations and the trades' pattern for working in small firms are some of the factors that make it difficult to introduce safe work practices in the construction industry (Jensen and Kofoed 2002). Breaking down the barriers to change requires education and instruction by people who know the trade and can effectively communicate with construction workers (Jensen and Kofoed 2002). For a new tool or work method to be accepted it must be easy to use, easy to understand and must fit into the culture of the trade. If these conditions are not met, the desired benefits may never be realized because the innovations were not given a fair chance due to the time pressures of construction work (Hess et al. 2004). The construction industry is a priority for research and interventions because of its high number of work related fatal and non-fatal injuries (Hoonakker et al. 2005). Tailored interventions have been shown to be effective in promoting health behavioral change in construction workers (Sorensen et al. 2007). A safety intervention is an attempt to change how things are done in construction companies in order to improve safety. Within the workplace it could be a new program, practice, or tool intended to protect the health and safety of employees (Robson et al. 2001).

Currently the main motivator for interventions in the construction industry is the concern for increased worker safety and health due to the injury and illness statistics published by OSHA and NIOSH. Construction work is unique in that it changes work conditions and workplaces. Most safety and health related issues in construction arise from the specific working conditions in the industry. To reduce the injury and health risks to workers, interventions educating workers about new PtD solutions and safety designs should be administered. Design for health means the elimination or reduction of worker exposure to potentially damaging physical agents that could be noise, vibration and dust (Vedder and Carey 2005). Better educated workers are more aware of the hazards that exist in the work environment. Appropriate training and education on health and safety is now widely recognized as a crucial factor in reducing and preventing injuries (Brunette 2005). Construction interventions should incorporate a theoretical basis for the design of the intervention, valid measurement instruments, and appropriate use of statistical analysis (Becker 2004). Most interventions in the area of construction safety and health have not been theory driven which limits the understanding of what interventions work and the variables and methods that are important to implement in their design. Theory driven interventions provide a conceptual framework for refining and improving existing hazard control measures as well as aiding researchers design studies that are repeatable and generalizable (Goldenhar 1996). Examples of workplace interventions that have used educational training sessions to improve worker behaviors include: agricultural workers use of hearing protection, skin cancer prevention for farm workers, ergonomic interventions dealing with musculoskeletal disorders in floor layers and concrete workers, and lead paint worker interventions (Goldenhar 1994; Parrott et al. 1996; Kirkhorn 2002; Materna 2002).

The ultimate success of construction safety interventions depends not only on the efficacy of the implemented change in safe work practices, but also on the willingness of workers

and employers to continue to utilize the practices in the field. The proposed change in work practice must appear reasonable to those who are asked to use it and it needs to be consistent (Hess et al. 2004). Change requires more from employees so they need help and support from management to be able to implement consistent changes (Beer 1990). Workers in the construction industry typically have received their training from experiences and values that have been passed down from earlier generations that are accepted as normal practices. Resistance to change is encountered because workers perceive that new innovations or work practices will at least for some period of time decrease their work intensity and output which correlates to their income. If changes in methods or new tools do not increase productivity or cannot be shown to be economically beneficial, it is difficult to motivate workers and employers to make changes (Jensen and Kofoed 2002).

Specific Aims

The following two Specific Aims were originally **proposed** for project DUSTI:

Aim 1: Develop an intervention strategy to improve dust-control technology transfer into the drywall-finishing industry. The intervention will target three separate populations: workers, owners of small firms, and owners of large firms; because, in our previous work, adoption barriers were found to differ among these three groups. The worker intervention will employ “cues to action” and training aimed at health information, risks, trust, and control technology. The small-firm intervention will employ the creation of “technology champions” within the firms and training aimed at productivity and customer satisfaction impacts, health information, and regulatory drivers. The large-firm intervention will involve information dissemination to purchasing agents aimed at communicating productivity and quality impacts, health information, and regulatory drivers.

Aim 2: Evaluate intervention strategy. A quasi-experimental design (pretest-posttest, with control group) will be employed to evaluate the intervention’s impacts on key theoretical constructs and barriers to adoption among workers, small-firm owners, and large-firm purchasing agents. The primary study hypothesis is that the following constructs will improve post-intervention: health knowledge, perceived risk, worker self efficacy, organizational trust, trust in the technology, adoption readiness, and perception of barriers.

These proposed aims were expanded and additional work was performed, beyond that which was proposed. The resulting five following Specific Aims were **completed** in the project period:

Aim 1: To develop a conceptual model to serve as the theoretical foundation for subsequent intervention design.

Aim 2: To design and validate survey instruments to measure key constructs of the conceptual model. Survey instruments in both English and Spanish, for workers and employers, are to be developed.

Aim 3: To design, implement, and evaluate an intervention strategy to improve overall adoption readiness among construction workers.

Aim 4: To design, implement, and evaluate an intervention strategy to improve overall adoption readiness among small contracting firm owners.

Aim 5: To design, implement, and evaluate an intervention strategy to improve overall adoption readiness among large construction firm purchasing decision makers.

All five of the above aims, which incorporated the two original aims and supplemented them with additional outcomes, were accomplished within a three-year project period. These five projects are described in detail in the following sections of this technical report. A section is devoted to each of the five Specific Aims.

Aim 1:

Conceptual Model Development

INTRODUCTION

Prevention through Design (PtD), eliminating hazards at the design-stage of tools and systems, is the optimal method of mitigating occupational health and safety (OHS) risks. A recent National Institute of Safety and Health initiative has established a goal to increase adoption of PtD innovation in industry. Therefore, as a first step toward improving adoption trends, a conceptual model, the Prevention through Design Adoption Readiness Model (PtD ARM), was developed to describe the parameters and causal relationships that influence and predict stakeholder “adoption readiness” for PtD technology innovation. Because this problem involves adoption of a health promoting technology, the model was built upon three well-established, related, theoretical frameworks: the Health Belief Model, the Diffusion of Innovation Model, and the Technology Acceptance Model. Earp and Ennett’s model development methodology was employed to build a depiction of the key constructs and directionality and magnitude of relationships among them. Key constructs were identified from the literature associated with the three theoretical frameworks, with special emphasis given to studies related to OHS technology adoption. A final conceptual model is presented. Recommendations for future research are described and include confirmatory structural equation modeling of model parameters and relationships, additional descriptive investigation of barriers to adoption in some trade sectors, and design and evaluation of an intervention strategy.

METHODS

Conceptual Model Development

Model development was performed according to the five-step methodology for conceptual model development established by Earp and Ennett (1991) and advanced by Carpiano and Daley (2006), which are:

1. Identify a theoretical framework, or sets of frameworks, that may explain phenomena of interest;
2. Identify important constructs. These are abstract concepts drawn from a theory. Constructs are used to guide the appropriate selection of observed measures or variables.
3. Detail the causal flow, which typically proceeds from left to right. Variables appearing to the left of the model are assumed to be causally antecedent to the variables appearing on the right.
4. Detail causal relationships using arrows.
5. Illustrate the direction of hypothesized causal relationships.

Identification of Theoretical Frameworks (Step 1)

Because the research described in this paper seeks to address a problem of adoption and diffusion of technology that is designed to improve health outcomes, well-established theoretical frameworks were chosen from the fields of health promotion, technology adoption, and innovation diffusion. These theoretical frameworks are highly interrelated and address from their own perspectives very similar outcomes: the decision to use new

practices or products. A framework integrating these theoretical models was needed to describe constructs that are pertinent to decision-making that is related to both health behavior and to technology adoption. Therefore, the PtD ARM was developed to describe this health behavior scenario that involves technological innovation.

Health Belief Model

The HBM was developed in effort to predict health-related attitudes and behaviors and has been applied to study all types of health behavior. The HBM has been used to explain both adoption (compliance) and maintenance (adherence) of behavior change. It has been employed in various configurations of the original model developed by social psychologists in the U.S. Public Health Service in the 1950's. (Hochbaum, 1958)(Rosenstock, 1974). The original HBM contained the following four key constructs:

1. Perceived susceptibility: an individual's assessment of their risk of getting the condition
2. Perceived severity: an individual's assessment of the seriousness of the condition and its potential consequences
3. Perceived barriers: an individual's assessment of the influences that interfere with or discourage adoption of the promoted behavior
4. Perceived benefits: an individual's assessment of the positive consequences of adopting the behavior

Subsequent to the Rosenstock version of the HBM, other authors added modifying factor constructs, which have been found to influence the perceptions described above. These are: demographic variables, socio-psychological variables, perceived self-efficacy, cues to action, health motivation, and perceived control.

Technology Acceptance Model

The Technology Acceptance Model (TAM) was developed by Davis (1989) to explain the factors that influence the decisions to accept or use new technology (Venkatesh, 2000). The TAM was originally designed to understand and predict user intentions to accept new computer technologies but has been used to understand technology acceptance in various fields of study including medical technology, communication systems, and information technology (Hu, 1999)(Chau, 1996)(Venkatesh, 2000)(Brown, 2002)(Yi et al, 2006). The TAM has been used to show that prospective adopters' behavioral intentions to use a technology correlate to the actual usage of the technology (Chau, 1996). If potential users do not fully accept the new technology, they can obstruct the new system and cause it to be underutilized (Brown, 2002). The TAM is comprised of two main constructs: perceived usefulness (PU) and perceived ease of use (PEOU) (Davis, 1989).

PU has been found to have a strong influence on perceptions of new technology (Chau, 1996). Davis (1989) further described perceived usefulness by showing six ways potential adopters judge the usefulness of a technology which include: (1) does the

technology allow the adopter to do the job more quickly? (2) Does using the technology improve the user's job performance? (3) Does using the technology increase productivity? (4) Does using the technology increase the effectiveness of the user's job? (5) Does using the technology make it easier for the user to do the job? (6) Does the user find the technology useful?

PU can have short-term implications to a user, such as improving job performance. It can also have long-term implications to a user, such as improving the user's status in the company over time or improving the user's health (Chau, 1996). Potential adopters form usefulness judgments by comparing what the new technology is capable of doing and what they need to get done to fulfill the requirements of their job. There are similarities between the PU construct of the TAM and the relative advantage construct in Rogers' diffusion of innovation model (Chau, 1996). An emphasis on PU and relative advantage will help in the design of effective interventions that promote acceptance of new technology (Venkatesh, 2000).

PEOU can also have a strong influence on acceptance of new technology. The perception that a technology is easy to use will have a direct effect on its acceptance, since technology viewed as being easy to use is more likely to be accepted (Davis, 1989). If a technology is viewed as easy to use, then the perceived level of usefulness has also been found to increase (Hu, 1999)(Brown, 2002). PEOU has been shown to have a smaller, but still significant, effect on user intentions to accept technology. This effect decreases over time, due to gains in self-efficacy with increased usage (Chau, 1996). PEOU is analogous to the construct of complexity from the diffusion of innovation model (Yi et al, 2006). The HBM construct of self-efficacy has also been compared to ease of use (Venkatesh, 2000)(Yi et al, 2006). The influence of PEOU is greater in organizational settings where adoption is mandatory; while, in voluntary settings, PU is the stronger determinant of intention to use technology (Brown, 2002).

Diffusion of Innovation Model

Rogers' Diffusion of Innovation is a model that describes diffusion as "the process by which an innovation is communicated through certain channels, over time, among the members of a social system." (Brown, 2002). Rogers theorized that innovations would spread through society in pattern that is normally distributed and that market saturation would be described by a logistic function. Innovators select the technology first, followed by "early adopters", and then the majority, until a technology or innovation is used commonly. The Rogers model is essentially a process of incremental learning and transfer of knowledge from the initial set of users to potential users. Innovation is defined as a significant improvement in a product, process or system that is new to those who will be developing or using it (Manseau and Shileds, 2005). One of the necessary components of an innovation is the ability of the innovation to improve some aspect of the adopter's performance of a work task (relative advantage)(Toole, 1998).

Much diffusion research has focused on the conditions that increase or decrease the likelihood that a new idea, product, or practice will be adopted by members of a given culture. The mechanism of diffusion is described as a five-step learning process: knowledge, persuasion, decision, implementation, and confirmation. In the knowledge stage, the person becomes aware of an innovation and has some idea of how it functions. In the persuasion stage, a favorable or unfavorable attitude toward the innovation is formed. In the decision phase, the person engages in activities that lead to a choice to adopt or reject the innovation. If the choice to adopt is made, then the implementation phase follows; in which, the person puts the innovation to use. The final stage is described as confirmation, wherein the user evaluates the results of the innovation.

Diffusion relies on the communication of information about the characteristics of innovations to potential adopters via a variety of networks. The logistic function reflects the bandwagon contagion effects of increased adoption. The earlier stages of diffusion, launch and early adoption, are more critical in establishing the overall trajectory of the diffusion curve. Many of the PtD innovations reviewed in this article are currently at the critical “launch” or “early adoption” stages of the diffusion cycle. The learning that occurs at these initial stages heavily influences the ultimate scale of the diffusion curve. Planned intervention, designed to increase adoption readiness at these early stages can enhance the overall diffusion trajectory and impact of the PtD on the construction industry.

Identification of Constructs (Step 2)

Overview

Constructs selected for inclusion in the integrated conceptual model are summarized in Table 6, and the rationale for their selection is provided in the sections that follow.

TABLE 6. Identified Model Constructs

Construct	Stakeholder Group	Description	Theoretical Framework
Perceived Susceptibility	Workers	Worker perception of personal likelihood of becoming ill	HBM

Perceived Severity	Workers	Worker perception of potential severity of health outcomes	HBM
Productivity	Owners	Perception of technology's impact on work output	TAM
Quality	Owners	Perception of technology's impact on work quality	TAM
Reliability	All	Perception of how reliably the technology will perform.	DOI
Perceived Barriers	All	Worker and owner perception of barriers to or associated with adoption	HBM
Perceived Benefits	All	Perception of benefits to be attained through adoption	All
Relative Advantage	Owners	Perception of how innovation will impact profitability of company	DOI
Trust in Technology	Workers	Belief in the value of and willingness to depend upon the technology	TAM
Perceived Usefulness	All	Perception of the benefits associated with use of technology	TAM
Trust in Organization	Workers	Belief in the honesty, fairness, and benevolence of the employer and organizational system	TAM
Perceived Ease of Use	All	Perception of difficulty or ease in using technology	TAM
Trialability	All	Opportunity for hands-on experience with the technology	DOI

Complexity	All	Complexity of human-technology interface	DOI
Observability	All	Opportunity for observation of technology in use	DOI

Health Belief Model Constructs

Perceived susceptibility, perceived severity, perceived benefits, perceived barriers (risks), and self-efficacy are all factors influencing the decisions people make to adopt behaviors that will lead to improved health outcomes (Wong and Tang, 2005). In a critical review of all Health Belief Model studies during the period 1974 to 1984, Janz and Becker (1984) found that "perceived barriers" proved to be the most powerful of the HBM dimensions across the various study designs reviewed. Therefore, that HBM construct is included in the PtD Model. Based on the findings of the Young-Corbett studies (2009, 2010), described earlier, the following constructs were selected for inclusion in the model: perceived disease susceptibility, perceived disease severity, self-efficacy, trust in technology, and trust in organization. These studies identified both worker and owner perceptions. Workers reported a low perception of personal susceptibility to disease and that self-efficacy and organizational trust were considered barriers to adoption. Owners identified trust in technology factors and low perception of health risk as barriers to adoption. In a framework linking health psychology to health outcomes, von Wagner et al (2009) make the case for the influence of knowledge and understanding on individual beliefs and attitudes of susceptibility and that perceived susceptibility is a determinant of health behavior change. Therefore, perceived susceptibility is a key construct chosen for inclusion in the model.

TAM Constructs

PU is defined as the degree a person believes that using the a new technology will increase their effectiveness or performance while PEOU is defined by the potential adopter's view of how much effort will be required to adopt the new technology (Davis, 1989). These two constructs of the TAM have been shown to be strong determinants of predicting adopter intentions to accept technology (Venkatesh, 2000). Trust in technology has also been associated with the TAM and has been found to have a direct influence on a behavioral intentions to use a technology and has a positive effect on the PU and PEOU constructs of the TAM (Wu and Chen, 2005). If a technology is perceived as useful, then trust in that technology is increased (Lippert, 2005). Therefore, PU and PEOU are selected for inclusion in the integrated conceptual model. Additionally, the model depicts anticipated relationships between these and modifying constructs, such as: trialability, complexity, observability, compatibility, trust, relative advantage, and reliability.

DOI Constructs

The characteristics of innovation that are responsible for influencing the rate of adoption are: relative advantage, compatability, complexity (ease of use), triability, and observability. Increasing perceived relative advantage, compatability, triability and observability; while decreasing the perceived complexity, will result in increased adoption (Rogers, 2002). According to Rodgers, 49-87 percent of the variance in adoption rate is explained by these characteristics (Rogers, 2003)(Vollink, 2002). Innovative individuals in social systems, known as opinion leaders or innovation champions, can influence the diffusion of innovation (Howell and Higgins, 1990). Preventative innovations have been perceived as having low relative advantage, when compared to other innovations that are designed to create a profit (Rogers, 2002). Perceived relative advantage has been found to be the most important predictor of the rate of diffusion for preventative innovation adoption (Rogers, 2003). Therefore, the constructs selected for inclusion in the integrated conceptual model are: perceived relative advantage of using the PtD technology, with regard to production capability and quality.

Detail of Causal Flow and Relationships (Steps 3 – 5)

Incorporated in the conceptual model are arrows indicating the major direction of influence of constructs on one another. Arrows point to constructs that are being influenced. Anticipated correlation magnitude is also indicated in the model, through plus and minus signs placed along the arrow lines, to indicate the nature of the anticipated relationship. For correlations that are anticipated to be positive or negative, + or – signs are used, respectively. For relationships between antecedent and predicted variables that are more complex, the +/- sign is employed to indicate the nature of that complexity.

RESULTS

A conceptual model, combining relevant constructs from the Health Belief Model, Technology Acceptance Model, and Diffusion of Innovation Model was constructed and is presented in Figure 4.

In the PtD ARM, “actual usage” is predicted by the construct “adoption readiness”, the model’s endogenous variable. “Adoption readiness” has several modifying antecedents: “self-efficacy”, “perceived ease of use”, “perceived usefulness”, and “trust in organization”. These constructs were extracted from the three foundational theoretical frameworks. All of these constructs are thought to positively correlate with the endogenous variable. In the model, “perceived usefulness” is thought to be modified by “trust in technology”, “relative advantage”, and “reliability”. “Perceived ease of use”, is thought to be modified by the “complexity” of the technology and whether the stakeholders have the chance to become familiar with the technology (“trialability” and

“observability”). “Self-efficacy” is thought to have modifying effects on “perceived ease of use”, as well. The HBM constructs of “perceived barriers” and “perceived benefits” are thought to influence stakeholder trust in the PtD technology. Perceptions of the severity of health outcomes and individual susceptibility to health outcomes will impact perceived benefits of adopting the health promoting technology.

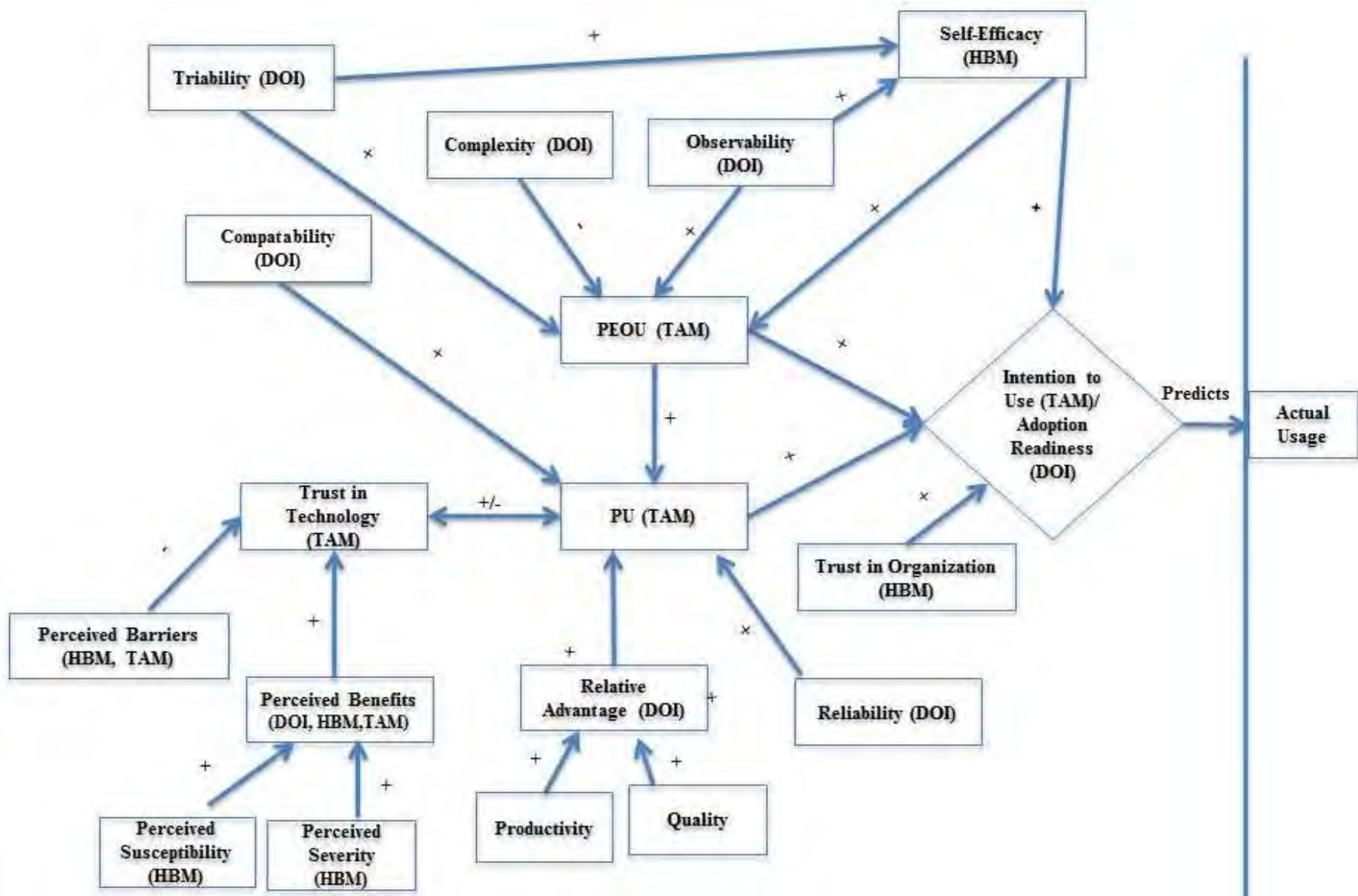


FIGURE 4: PtD Adoption Readiness Model (PtD ARM)

CONCLUSION

By taking an integrative approach, the PtD Adoption Readiness Model (PtD ARM) enhances our understanding of the interrelationships of complementary model constructs and factors that influence user adoption intentions of technology innovation, specifically as related to technology that is designed to prevent worker illness. PtD ARM is the first to integrate the HBM, TAM, and DOI frameworks into a synthesized conceptual model for explaining or predicting behavioral intentions to adopt new technology. As there are documented instances of commercially available, yet poorly diffused, PtD technologies for preventing illness, injury and fatality in the construction industry, a model that can be employed to drive intervention development was needed. Since the U.S. National PtD initiative has, as one of its major goals, the improved diffusion and adoption of these innovations, the PtD ARM could be useful as a foundation for future diffusion intervention strategies and activities.

Aim 2:

Validated Survey Instruments

INTRODUCTION

Two survey instruments were developed based on the Prevention through Design Adoption Readiness Model (PtD ARM). These instruments were designed to measure constructs of the PtD ARM and were employed in pre-test/post-test study design of intervention effectiveness. Two instruments were developed: one for construction workers and one for firm owners. This section describes the rigorous development and validation process employed and presents the resulting survey instruments.

METHODS

Overview

The development of the PtD ARM survey instruments was performed via a rigorous process, involving three phases: 1) construct operationalization, 2) cognitive testing, and 3) validation and reliability testing. Each of these phases is described in detail, below.

Construct Operationalization

Previously Validated Scales and Indices

Because the PtD ARM was constructed from three well-established conceptual models, the Technology Acceptance Model (TAM), the Diffusion of Innovation Model (DOI), and the Health Belief Model (HBM), the research team searched the extant scholarly literature for scales, indices, and survey instruments based upon these models. Only those instruments that had been subjected to rigorous development and validation protocols were selected for review. Additionally, only those that seemed most applicable for adaptation to the present use were selected for the final set. These included Champion's Health Belief Model scales⁽⁷⁾, Parasuraman's Technology Readiness Index (TRI)⁽⁸⁾, The Self Efficacy Scale (SES) by Sherer and Maddux⁽⁹⁾, Robinson's Trust Scale⁽¹⁰⁾, Venkatesh's Technology Acceptance Model instrument⁽¹¹⁾, and Armenakis' Change Readiness Scale⁽³⁾. Champion's HBM scale contains items to measure perceived risk, benefits, barriers, and motivation. The TRI contains items pertaining to the constructs of "readiness" and "innovativeness", which were adapted for the current instrument. The SES contains items pertaining to self-efficacy, which were adapted for the PtD ARM instrument. Specifically, items pertaining to the constructs "personal control", "competency", and "self-esteem" were selected for inclusion. Robinson's Trust Scale contained items pertaining to organizational trust and a worker's trust in the employer. Venkatesh was the first to operationalize the TAM constructs: "perceived ease of use" and "perceived usefulness" and that author's instrument has been subjected to rigorous field validation by numerous investigators. And, Armenakis' scale contains specific items for assessing "adoption readiness". From these previously validated instruments, items pertaining to the PtD ARM constructs were selected for adaptation and modification into language that pertains to the drywall finishing trade sector.

Initial Item Set

From the previously validated scales and instruments, an initial item set was produced for the PtD ARM instrument. This set contained 58 items, which were intended to measure the following constructs: perceived health risk (10), trust in organization (8), trust in technology (6), self-efficacy (8), adoption readiness (7), perceived ease of use (10), and perceived usefulness (9). This set of items was subjected to an iterative refinement process, which eventually yielded our final set of 38 items for the two instruments: 20 for the employer instrument and 18 for the worker instrument. The refinement stages are described, below.

Card Sort Technique

Construct operationalization was further evaluated through item-construct correspondence. The item-construct correspondence was evaluated through an evaluative, closed, card-sorting procedure. In a closed card sort, participants are provided with a deck of cards which contain phrases and a predetermined set of category names. They then assign the index cards to these fixed categories. This helps reveal the degree to which the participants agree on which cards belong under each category. Closed sorting is evaluative; it is typically used to judge whether a given set of category names provides an effective way to organize a given collection of content. In this study, a group of ten participants individually performed the card sorting technique. These participants were graduate students in the building construction program at Virginia Tech. Each was given a stack of cards with one survey instrument item printed on each. On the table were papers indicating the constructs of the PtD ARM model. Participants were asked to place the cards on the construct name they felt most closely matched the statement on the card. All construct categories were assigned a numerical code, so that inter-rater reliability could be assessed using Krippendorff's alpha coefficient. Those instrument items having reliability of $\alpha \leq 0.80$ were removed from the item pool.

Cognitive Testing

Collins (2003) argues that an important phase of survey instrument development is to perform an assessment of the question-and-answer process involved in the completion of the survey instrument and that cognitive methods are ideal for fulfilling this function. It is essential to determine if an instrument item is meeting its intended purpose and, if not, to understand “how” and “where” it is failing.⁽¹²⁾ Cognitive methods, from social psychology, allow researcher to explore the processes by which respondents answer questions.

Subject Matter Expert (SME) Review

The initial item pool was reviewed by two types of SME: those with expertise in survey instrument development and those with expertise in construction operations. Researchers in the Virginia Tech Center for Survey research composed the first set of SME reviewers. These SMEs possess knowledge of psychometrics and design of surveys, tests, and instruments. They were asked to review the item pool and make comments on any problematic items, in terms of item construction. The second set of SMEs were employers and workers in the drywall trade. They were asked to review the items and identify any problems in language, terminology,

understandability, and relevance. The SME feedback provided valuable insight into common trade terminology and several items were eliminated from the pool or revised.

Probing Cognitive Interviews

In this phase of the study, members of the Myers-Lawson School of Construction Industry Board and workers from Southwestern Virginia were asked to participate in cognitive interviews. The cognitive interviewing approach to evaluating sources of response error in survey questionnaires was developed during the 1980's through an interdisciplinary effort by survey methodologists and psychologists. It explicitly focuses on the cognitive processes that respondents use to answer survey questions; therefore, covert processes that are normally hidden, as well as overt, observable ones, are studied. Probing cognitive interviewing is the technique that has increasingly come into favor by cognitive researchers.⁽¹³⁾ After the interviewer asks the survey question and the participant answers, the interviewer asks for additional information relevant to the question, or to the specific answer given. In general, the interviewer "probes" further into the basis for the response.

To evaluate the PtD ARM item pool, six male participants, three who were in management positions in the commercial construction industry, and three who were laborers in the drywall trade, agreed to participate. The management group reviewed the "Employer Instrument" item set. The laborer group reviewed the "Worker Instrument" item set. The cognitive interviews followed a standardized protocol. A member of the research team met with the participant and asked him to read each item to himself. Then, the participant was asked to paraphrase the item in his own words. The researcher then followed up with probing questions from a set of possible probes: "what does term X mean to you?"; "I noticed you hesitated before answering, can you tell me what you were thinking about?"; "how easy/difficult did you find this question to answer?"; "why was that?"; and, "was there anything confusing about this question?". The cognitive interviews were audio-recorded and reviewed by the research team at a subsequent time. The interviews identified several items that were lacking in clarity or that were answered in an unintended manner. These items were eliminated from the item pool.

Validation and Reliability Testing

This phase of instrument development includes specific assessment of convergent validity and discriminant validity and the prerequisite unidimensionality and reliability. Validity and reliability testing methods employed in the development of the PtD ARM survey instrument are summarized in Table 7 and described in this section.

TABLE 7: Reliability and Validity Measures

Criterion	Test Employed	Interpretation
Unidimensionality	Confirmatory Factor Analysis (CFA)	GFI $\geq$ 0.80

Reliability	Cronbach's reliability coefficient (α)	$\alpha \geq 0.600$
Convergent Validity	Bentler-Bonett coefficient (Δ)	$\Delta \geq 0.800$
Discriminant Validity	Average Interscale Correlation	Differs from 1
	Item-to-total Correlation	Differs from interscale

Data Collection

Draft versions of the two PtD ARM instruments were developed and were employed to collect data for the purpose of reliability and validity testing of the instruments. At this phase, the Employer Instrument contained 26 items and the Worker Instrument contained 28 items, both employing a Likert-type, 7-point scale with anchors: "1 = Strongly Disagree" and "7 = Strongly Agree". At the American Wall and Ceiling Institute (AWCI) 2011 annual convention in Las Vegas Nevada, 50 drywall professionals completed each of the two questionnaires ($n = 100$). Participants were compensated ten dollars apiece for their time and were provided with Human Subject disclosure information. All protocols were approved by the Virginia Tech Institutional Review Board. Data were utilized to evaluate the unidimensionality, reliability, convergent and discriminant validity of the instrument constructs and scales.

Data Analysis

Unidimensionality is the extent to which observed indicators are strongly associated with each other and represent a single concept. Unidimensionality is a necessary condition for reliability analysis and construct validation. Unidimensionality can be assessed in various ways. In this study, we employed confirmatory factor analysis (CFA) to test the construct measurement model. A goodness of fit index (GFI) exceeding 0.90 indicates strong unidimensionality. In the case of complex model development exploratory phase, as is the case in the current paper, some authors have suggested that an index as low as 0.80 can be used as a minimum threshold for unidimensionality.⁽¹⁴⁾ Therefore, in the current study, a GFI index greater than or equal to 0.80 was considered to be an indication of item unidimensionality.

Once the unidimensionality of scales is established, an assessment of the statistical reliability is necessary before any further validation. Reliability refers to the degree of consistency or stability of a scale.⁽¹⁵⁾ If the items of a scale account for a significant part of the variation in the construct versus measurement error, the scale is said to be reliable. In order to establish the reliability of the PtD ARM instruments, Cronbach's reliability coefficient (α) was employed. While there is no strict threshold for high reliability, several values have been widely accepted in the literature. Nunnally⁽¹⁶⁾ recommends two thresholds, 0.50 for early exploratory work on constructs and 0.70 for established scales. Many researchers have used 0.60 for emerging scales and 0.70 for established scales.⁽¹⁷⁾ Since the PtD ARM instruments are emerging and undergoing development, but are based upon established and well-validated existing scales, the 0.60 threshold for Cronbach's alpha was employed in the current work.

Convergent validity is the extent to which varying approaches to construct measurement yield the same results.⁽¹⁸⁾ One method of accomplishing this is to treat the individual items on the instrument as separate methods of measuring the same construct. Thus, the extent of convergence of the set of items on the construct can be assessed.⁽¹⁹⁾⁽²⁰⁾⁽²¹⁾ To assess the convergent validity of the PtD ARM instrument items on the model constructs, the current study employed the Bentler-Bonett coefficient (Δ), the ratio of the difference between the chi-square value of the null measurement model and the chi-square value to the specified measurement model to the chi-square value of the null model. Values of Δ between 0.80 and 0.90 are acceptable, though a value greater than 0.90 demonstrates strong convergent validity.

Finally, discriminant validity is assessed following the tests for convergent validity. Discriminant validity assesses the extent to which a construct and its indicators differ from another construct-item set. Adequate discriminant validity is established when Cronbach's reliability coefficient of each of the item scales is adequately larger than the average of the correlations among all model constructs. In the present paper, discriminant validity is assessed using the Average Interscale Correlation Test, the Item-total Correlations Test, and the Percent Variance Extracted test.

RESULTS

The item set was tested for unidimensionality, reliability, convergent and discriminant validity and only those items that met the threshold values (discussed in Methods section) were kept in the final item pool for the instruments. Any items not meeting the pre-determined interpretive thresholds were removed from the item pool. The results of the statistical reliability and validity testing for the final item set are presented in Table 8.

TABLE 8: Reliability and Validation Testing Results

	UNIDIM	RELIABILITY	CONV.	DISCRIMINANT VALIDITY		
				Interscale Correlation	Item-to-total Correlations	Percent Variance

CONSTRUCT	GFI	α	Δ	AVIS C	α -AVIS C	SCIT C	NSCIT C	SCIC-NSCI C	PVE	PVE/100 – AVISC ²
PR	0.91	0.847	0.980	0.434	0.423	0.645	0.355	0.290	59.01	0.402
TO	0.88	0.701	0.810	0.442	0.367	0.575	0.361	0.214	52.01	0.325
TT	0.82	0.798	0.856	0.305	0.441	0.579	0.247	0.332	66.40	0.571
SE	0.98	0.964	0.917	0.466	0.332	0.622	0.384	0.238	63.89	0.422
PEOU	0.89	0.816	0.950	0.336	0.574	0.798	0.270	0.528	78.94	0.677
PU	0.95	0.869	0.965	0.295	0.669	0.899	0.237	0.662	87.70	0.790
PU-Q	0.96	0.721	0.884	0.443	0.385	0.606	0.365	0.241	55.14	0.355
PU-P	0.97	0.824	0.945	0.428	0.388	0.624	0.353	0.271	60.22	0.419
AR	0.94	0.943	0.913	0.344	0.430	0.697	0.369	0.328	66.09	0.455

Constructs: PR = Perceived Risk to Health; TO = Trust in Organization; TT = Trust in Technology; SE = Self-efficacy; PEOU = Perceived Ease of Use; PU = Perceived Usefulness; PU-Q = Perceived Usefulness-Quality; PU-P = Perceived Usefulness-Productivity; AR = Adoption Readiness

Tests: GFI = Goodness of Fit Index; α = Chronbach's reliability index; Δ = Bentler-Bonnett convergent validity coefficient; AVISC = Average interscale correlation; SCITC = Item to total correlations test; PVE = Percent variance extracted test

The final sets of items for both the Worker Instrument and the Employer Instrument are provided, along with the constructs they operationalize, in Table 9.

TABLE 9: Final Instrument Items

Construct	Instrument	Items
Perceived Risk	Worker	Serious health problems can result from working around dust
		I am worried about being exposed to drywall dust
		Working around drywall dust puts me at risk for health problems
	Employer	Components of drywall dust can cause health problems
		Components of drywall dust can cause health problems
		Exposure to drywall dust poses a potential health risk to workers

		Serious health problems can result form working around drywall dust
		My employees are susceptible to major health problems from exposure to drywall dust
		Working in the drywall industry is a rks factor for certain illnesses
Trust in Organization	Worker	I trust my employer to protect me from hazards I believe my employer is open and up-front with me I fully trust my employer I believe my employer's intentions and motives are good
Trust in Technology	Worker	Vacuum sanders are good tools to use when sanding drywall I trust vacuum sanders Using a vacuum sander improves my job performance I feel vacuum sanders can lower the amount of dust I am exposed to
Self Efficacy	Worker	I feel confident in my ability to use a vacuum sander I am the one who gets to choose whether to use a vacuum sander I have control over the decision to use a vacuum sander It would be easy for me to become skilled at using a vacuum sander
Perceived Ease of Use	Employer	My employees could effectively use vacuum sanders Vacuum sanders are too complex It will take a long time for my employees to learn to use vacuum sanders Vacuum sanders are difficult to use Vacuum sanders are easy to use
Perceived Usefulness	Employer	Vacuum sanders are good tools to use for sanding drywall I trust that vacuum sanders will do a good job
Subscales:		
Quality (Q),		Using a vacuum sander improves the quality of drywall finishes When using vacuum sanders, less dust is produced Vacuum sanders produce quality drywall finishes

Productivity (P)		Using a vacuum sander increases productivity
		Vacuum sanders save my company time
		It is convenient to use vacuum sanders
Adoption Readiness	Worker	Assuming I have access to a vacuum sander, I intend to use it
		If I have access to a vacuum sander, I want to use it as much as possible
	Employer	I anticipate my company will use (or continue to use) vacuum sanders
		My company always tries to use vacuum sanders in as many cases as possible

CONCLUSIONS

Two survey instruments were developed and validated for evaluating constructs of the Prevention through Design Adoption Readiness Model (PtD ARM). Items were created to measure the following constructs: Perceived Risk to Health, Trust in Organization, Trust in Technology, Self-Efficacy, Perceived Ease of Use, Perceived Usefulness (including subscales for Quality and Productivity) and Adoption Readiness.

Aim 3:

Worker Intervention Development, Implementation, Evaluation

INTRODUCTION

An intervention strategy was designed, based upon the PtD ARM constructs of relevance to the worker stakeholder group within the construction industry: perceived risk to health, health knowledge, trust in organization, trust in technology, self-efficacy. Influencing these antecedent constructs, it was hypothesized, would influence overall readiness to adopt the technology.

Table 10: Worker Intervention Design Constructs

Intervention Theoretical Target Constructs		
Worker Intervention	Small Firm Intervention	Large Firm Intervention
Perceived Risk to Health (HBM)	Perceived Risk to Health (HBM)	Perceived Risk to Health (HBM)
Health Knowledge (HBM)	Health Knowledge (HBM)	Health Knowledge (HBM)
Trust in Organization (TAM)	Perceived Usefulness (TAM, DOI)	Perceived Usefulness (TAM, DOI)
Trust in Technology (TAM)	Perceived Ease of Use (DOI, TAM)	Perceived Ease of Use (DOI, TAM)
Adoption Readiness/Intent to Adopt (DOI, TAM)	Trust in Technology (TAM)	Trust in Technology (TAM)
Self-Efficacy (HBM)	Adoption Readiness/ Intent to Adopt (DOI, TAM)	Adoption Readiness/ Intent to Adopt (DOI, TAM)

The intervention focused on two components: training and cues to action. The worker intervention consisted of a combination of didactic training and interactive training. The intervention aimed at improving the following constructs in relation to worker safety and health: perceived risk of drywall dust to personal health, health knowledge about the effects of drywall dust, trust in organization, trust in technology, adoption readiness and self-efficacy.

A training presentation program was developed that included information about the material composition of drywall dust, the health problems dust could potentially cause, the usefulness and relative advantage of using vacuum sanders which was aimed at influencing worker's perceived views of the usefulness of the tools. The information was assembled from previous studies regarding worker exposure and health outcomes, disease trends in the drywall finishing industry, available engineered technologies and methods for dust-control. Along with health and technology information, workers received a hands-on training with the vacuum sander aimed to enhance worker self-efficacy and trust in technology. The workers and small firms received handouts at the end of the training that provided basis for the materials covered. This hands-on training attempted to educate the workers on how the system works and to give them experience with its effectiveness. Triability is an element of the DOI that relates to the construct of perceived ease of use from the TAM and enhances the self-efficacy construct of the HBM which all influence a potential adopter's decision to adopt. Workers are prone to sometimes disuse or misuse technology if not properly trained or have not used certain methods that may reduce the

trust in the technology. The more someone understands how a technology works, the more likely they are to trust the technology (Dzindolet et al. 2003).

Two “cues to action” were developed as part of the intervention strategy (Figure 5). Cues to action are prompts that remind people to take action to practice certain behaviors that will protect their health. Incorporating cues to action into the worker intervention helped to provide a stimulus to participants and serve as a reminder to practice safe behavior. Cues to action can be realized in a variety of forms but should be elicited from potential cues that the participant is exposed to on a regular basis. Cues that could be used are visible cues such as hard hat stickers, t-shirts, posters, or could come from non-visible sources such as experiences with family or other workers (Elder 1999). For this intervention, cues that workers can see regularly were used so the behavior could be reinforced often. The first cue to action was t-shirts the workers were given and could wear regularly to remind them and their co-workers of the hazards associated with drywall dust exposure and the importance of using dust-control technology to protect them from over-exposure to dust. The second cue to action was hard hat stickers aimed at reminding workers to use dust control technologies. These cues attempted to serve as a motivation to employees to implement dust control methods to improve their health and quality of life. Drywall sanders who use PtD solutions will be less likely to require respiratory protection, they will be less irritated by airborne drywall dust and should be more comfortable, more alert and more productive (Mead et al. 1995).



Figure 5. Worker Cues to Action (t-shirt and hard-hat sticker)

Participants included recruited workers from a convenience population of Virginia and North Carolina. These participants were recruited based on the recommendation of drywall supply companies in Virginia and North Carolina. There were 40 worker participants, 20 who received the intervention and 20 who served as a control group. Participants were recruited as volunteer participants as such they could have elected to drop out of the study at any time (Goldenhar 1996). All participants in the employee groups were compensated in the amount of fifteen dollars an hour for their participation.

The intervention implementation began with a member of the research team gaining consent from the participants and explaining that the participant's identity will remain anonymous followed by a pre-test for all participants administered by a member of the research team. Once the interventions were administered, the participants were then given the posttest. Following the interventions and initial control surveys, attempts were made to contact all participants again three months following the intervention and were given the same posttest. When measuring changes in employee knowledge and attitudes after a training session, measurements should be taken prior to the intervention, immediately after the intervention and around three months following the intervention to see if the intervention has a lasting effect on the participants (Feldman et al. 2004).



Figure 6. Research Design Worker Intervention

Worker Intervention Implementation

The Worker intervention began with a member of the research team contacting drywall companies based on the recommendations of local drywall suppliers. The researchers obtained consent from the drywall companies to contact their workers who were then recruited as volunteer participants who acted as control participants or receive the intervention. Participants were compensated in the amount of fifteen dollars an hour. Consenting employers were encouraged to participate in the employer interventions. The participants were randomly assigned as either control group or intervention group participants and given a pretest as a basis for evaluation of the intervention. The control participants contact information was taken and attempts were made to contact participants again after 3 months to take the posttest. Intervention

participants were given the intervention immediately following the pretest and then attempts were made to contact participants to administer a posttest after 3 months.

The interventions were held at the jobsites where the employees were working so that practical hands on experience could be demonstrated in the training and disruption of employer operations could be minimized. The training was worker centered with hands on training that attempted to motivate employees to remain active in improving their safe working conditions (Becker 2004). An authorized OSHA outreach trainer with experience in teaching construction safety topics administered the training sessions in this intervention. Interactive small group training was used, as this method has been strongly associated with achieving desired changes in work practices (Goldenhar 2001). The implementation involved increasing worker knowledge about working around drywall dust and how to control the hazard, attempting to decrease negative perceptions about the control methods and allowing them to practice using the tools to gain self-efficacy (Parrott et al. 1996). The intervention included a short educational training focusing on content about the potential health effects of drywall dust based on past studies found in the literature review, information about the OSHA regulations for exposure to drywall dust, and information about the use and effectiveness of the various PtD options available for controlling dust exposure. The trainer then showed how to properly use the vacuum sander and highlighted the safety features of the tool. Employees were then given the opportunity to practice with the sanders to apply what they learned in the training on their projects. All workers received a certificate of training to acknowledge they have received health and safety training from an OSHA authorized trainer. This certificate was aimed to enhance the credibility of the training and provided employers added training documentation OSHA regulations require employers to keep. As part of the worker intervention materials, T-shirts and hardhat stickers were also given to the workers to serve as cues to action reminding the workers of the training received and the actions they need to take to protect their health.

Data Collection and Analysis

The employee survey instrument (Appendix) was administered as the pre and post-test to all employee participants. Constructs measured were: Health Knowledge, Perception of Risk, Self Efficacy, Trust in Technology, Trust in Organization and Adoption Readiness. Questions designed to measure each construct were grouped according to construct and each construct was examined against the null hypothesis to determine if the interventions had any significant impact on the constructs.

Each question response was scored as a 7 point Likert Scale question with possible answers scaled as follows: 1= strongly disagree, 2 disagree, 3 somewhat disagree, 4 neither disagree or agree, 5 somewhat agree, 6 agree, 7 strongly agree and 0 N/A. The question groupings by construct are shown in Table 17. Results were compiled for each round for each construct and a independent T test was run using the JMP 9.0.0 statistical software to compare the difference in

mean scores between intervention group and control group participant responses for each construct.

Demographics of the sample population for employees was based on the United States Bureau of Labor Statistics labor force reports where 49% of drywall employees were listed as Hispanic (Bureau of Labor Statistics 2008). Based on this information, half of the 20 participants from both the intervention and control groups were from the Hispanic workforce. Participant surveys in English and Spanish were made available for all participants.

Intervention Evaluation

The employee survey instrument (Appendix) was administered as the pre and post-test to all employee participants. Constructs measured were: Health Knowledge, Perception of Risk, Self Efficacy, Trust in Technology, Trust in Organization and Adoption Readiness. Questions designed to measure each construct were grouped according to construct and each construct was examined against the null hypothesis to determine if the interventions had any significant impact on the constructs. Each question response was scored as a 7 point Likert Scale question with possible answers scaled as follows: 1= strongly disagree, 2 disagree, 3 somewhat disagree, 4 neither disagree or agree, 5 somewhat agree, 6 agree, 7 strongly agree and 0 N/A. The question groupings by construct are shown in Table 17. Results were compiled for each round for each construct and a gain-score analysis of variance was performed using JMP 9.0.0 statistical software to compare the difference in mean scores between intervention group and control group participant responses for each construct.

The following hypotheses were examined to determine intervention effectiveness.

Null Hypothesis 1= Post-test gain scores of **health knowledge** for worker intervention participants will be no different than post-test scores in the worker control group for post-test 1 and post-test 2.

Null Hypothesis 2= Post-test gain scores of **self-efficacy** for worker intervention participants will be no different than post-test scores in the worker control group for post-test 1 and post-test 2.

Null Hypothesis 3= Post-test gain scores of **perceived risk** for worker intervention participants will be no different than post-test scores in the worker control group for post-test 1 and 2.

Null Hypothesis 4= Post-test gain scores of **trust in technology** for worker intervention participants will be no different than post-test scores in the worker control group for post-test 1 and post-test 2.

Null Hypothesis 5= Post-test gain scores of **trust in organization** for worker intervention participants will be no different than post-test scores in the worker control group for post-test 1 and post-test 2.

Null Hypothesis 6= Post-test gain scores of **adoption readiness** for worker intervention participants will be no different than post-test scores in the worker control group for post-test 1 and post-test 2.

A summary of the employee intervention evaluation results, based on a gain score analysis measuring each construct is shown in Table 11. Individual construct statistical results are reported in more detail in the sections that follow.

Table 11. Employee Intervention Construct Gain Score Summary

Employee Intervention Results Summary			
Gain Score ANOVA			
Construct Measured	Gain Score p value	Significant at .05 level	Significant at .10 level
Health Knowledge Post-Test 1	0.989		No
Health Knowledge Post-Test 2	0.826	No	No
Self-Efficacy Post-Test 1	0.100	No	No
Self-Efficacy Post-Test 2	0.050	No	Yes
Perceived Risk Post-Test 1	0.621	No	No
Perceived Risk Post-Test 2	0.612	No	No
Trust in Technology Post-Test 1	0.05	No	Yes
Trust in Technology Post-Test 2	0.21	No	No
Trust in Organization Post-Test 1	0.802	No	No
Trust in Organization Post-Test 2	0.5939	No	No
Adoption Readiness Post-Test 1	0.018	Yes	Yes
Adoption Readiness Post-Test 2	0.566	No	No

Employee Health Knowledge

Based on the results (Independent Sample $t = .0132$, $df=49$, $p>.989$) the null hypothesis is not rejected at both the .05 and .1 levels. There is no significant evidence that the intervention had any effect on increasing gain scores from pre-test to *post-test 1* of health knowledge among intervention participants.

Table 12. Employee Health Knowledge Post-Test 1 Results

Gain Score ANOVA Pre-Test to Post-Test 1

Construct: Health Knowledge

Difference	0.0101	t =	0.013152		
Std Err Dif	0.768	DF	49		
Upper CL Dif	1.5535	p =	0.9896		
Lower CL Dif	-1.5333	Prob > t	0.4948		
Confidence	0.95	Prob < t	0.5052		
Group	Number	Mean	Std Error	Lower 95%	Upper 95%
Control	18	1.44444	0.61779	0.20295	2.6859
Intervention	33	1.45455	0.45627	0.53764	2.3714

Based on the results (Independent Sample $t = -.22$, $df=36$, $p=.826$) the null hypothesis is not rejected at both the .05 and .1 levels. There is no significant evidence that the intervention had any effect on increasing gain scores from pre-test to the *second post-test* of health knowledge among intervention participants.

Table 13. Employee Health Knowledge Post-Test 2 Results

Gain Score ANOVA Pre-Test to Post-Test 2

Construct: Health Knowledge

Difference	-0.1944	t Ratio	-0.22092		
Std Err Dif	0.8801	DF	36		
Upper CL Dif	1.5906	Prob > t	0.8264		
Lower CL Dif	-1.9794	Prob > t	0.5868		
Confidence	0.95	Prob < t	0.4132		
Group	Number	Mean	Std Error	Lower 95%	Upper 95%
Control	18	1.44444	0.63852	0.14947	2.7394
Intervention	20	1.25	0.60575	0.02148	2.4785

Employee Self-Efficacy

Based on the results (Independent Sample $t = 1.674$, $df=49$, $p=.1005$) the null hypothesis is not rejected at both the .05 and 0.1 levels. There is no significant evidence that the intervention had any effect on increasing gain scores from pre-test to *post-test 1* of self-efficacy among intervention participants for the first post-test.

Table 14. Employee Self-Efficacy Post-Test 1 Results

Gain Score Anova Pre-Test to Post-Test 1					
Construct: Self-Efficacy					
Difference	1.8384	t Ratio	1.673964		
Std Err Dif	1.0982	DF	49		
Upper CL Dif	4.0453	Prob > t	0.1005		
Lower CL Dif	-0.3686	Prob > t	0.0503		
Confidence	0.95	Prob < t	0.9497		
Group	Number	Mean	Std Error	Lower 95%	Upper 95%
Control	18	-0.1111	0.88341	-1.886	1.6642
Intervention	33	1.7273	0.65244	0.416	3.0384

Based on the results (Independent Sample $t = 2.027$, $df = 36$, $p = .0501$) the null hypothesis is not rejected at the .05 level and rejected at the 0.1 level. There is significant evidence at the 0.1 level that the intervention did have an effect on increasing gain scores from pre-test to the *second post-test* of self-efficacy among intervention participants.

Table 15. Employee Self-Efficacy Post-Test 2 Results

Gain Score Anova Pre-Test to Post-Test 2					
Construct: Self-Efficacy					
Difference	2.0611	t Ratio	2.026713		
Std Err Dif	1.017	DF	36		
Upper CL Dif	4.1236	Prob > t	0.0501		
Lower CL Dif	-0.0014	Prob > t	0.0251		
Confidence	0.95	Prob < t	0.9749		
Group	Number	Mean	Std Error	Lower 95%	Upper 95%
Control	18	-0.1111	0.73779	-1.607	1.3852
Intervention	20	1.95	0.69993	0.53	3.3695

Employee Perceived Health Risk

Based on the results (Independent Sample $t = .498$, $df = 49$, $p = .6207$) the null hypothesis is not rejected at both the .05 and 0.1 levels. There is no significant evidence that the intervention had any effect on increasing gain scores from pre-test to *post-test 1* of perceived health risk among intervention participants.

Table 16: Employee Perceived Risk to Health Post-Test 1 Result

Gain Score Anova Pre-Test to Post-Test 1					
Construct: Perceived Risk to Health					
Difference	0.4444	t Ratio	0.498062		
Std Err Dif	0.8923	DF	49		
Upper CL Dif	2.2377	Prob > t	0.6207		
Lower CL Dif	-1.3488	Prob > t	0.3103		
Confidence	0.95	Prob < t	0.6897		
Group	Number	Mean	Std Error	Lower 95%	Upper 95%
Control	18	1.22222	0.7178	-0.2203	2.6647
Intervention	33	1.66667	0.53013	0.6013	2.732

Based on the results (Independent Sample $t = .512$, $df = 36$, $p = .6115$) the null hypothesis is not rejected at both the .05 and 0.1 levels. There is no significant evidence that the intervention had any effect on increasing gain scores from pre-test to the *second post-test* of perceived health risk among intervention participants.

Table 17: Employee Perceived Risk to Health Post-Test 2 Results

Gain Score Anova Pre-Test to Post-Test 2					
Construct: Perceived Risk to Health					
Difference	0.4278	t Ratio	0.512448		
Std Err Dif	0.8348	DF	36		
Upper CL Dif	2.1208	Prob > t	0.6115		
Lower CL Dif	-1.2652	Prob > t	0.3057		
Confidence	0.95	Prob < t	0.6943		
Group	Number	Mean	Std Error	Lower 95%	Upper 95%
Control	18	1.22222	0.60561	-0.006	2.4505
Intervention	20	1.65	0.57453	0.4848	2.8152

Employee Trust in Technology

Based on the results (Independent Sample $t = 2.006$, $df = 49$, $p = .0504$) the null hypothesis is not rejected at the .05 level and is rejected at the 0.1 level. There is significant evidence at the 0.1 level that the intervention was effective at increasing gain scores from pre-test to *post-test 1* trust in technology among intervention participants.

Table 18: Employee Trust in Technology Post-Test 1 Results

Gain Score Anova Pre-Test to Post-Test 1					
Construct: Trust in Technology					
Difference	2.0505	t Ratio	2.005978		
Std Err Dif	1.0222	DF	49		
Upper CL Dif	4.1047	Prob > t	0.0504		
Lower CL Dif	-0.0037	Prob > t	0.0252		
Confidence	0.95	Prob < t	0.9748		
Group	Number	Mean	Std Error	Lower 95%	Upper 95%
Control	18	0.55556	0.82226	-1.097	2.2079
Intervention	33	2.60606	0.60728	1.386	3.8264

Based on the results (Independent Sample $t = 1.276$, $df = 36$, $p = .21$) the null hypothesis is not rejected at both the .05 and 0.1 levels. There is no significant evidence that the intervention had any effect on increasing gain scores from pre-test to the *second post-test* of trust in technology among intervention participants.

Table 19: Employee Trust in Technology Post-Test 2 Results

Gain Score Anova Pre-Test to Post-Test 2			
Construct: Trust in Technology			
Difference	1.9444	t Ratio	1.276427

Std Err Dif	1.5233	DF	36		
Upper CL Dif	5.0339	Prob > t	0.21		
Lower CL Dif	-1.1451	Prob > t	0.105		
Confidence	0.95	Prob < t	0.895		
Group	Number	Mean	Std Error	Lower 95%	Upper 95%
Control	18	0.55556	1.1052	-1.686	2.7969
Intervention	20	2.5	1.0484	0.374	4.6263

Employee Trust in Organization

Based on the results (Independent Sample $t = .2527$, $df=49$, $p=.8015$) the null hypothesis is not rejected at both the .05 and 0.1 levels. There is no significant evidence that the intervention had any effect on increasing gain scores from pre-test to *post-test 1* of trust in organization among intervention participants.

Table 20: Employee Trust in Organization Post-Test 1 Results

Gain Score Anova Pre-Test to Post-Test 1					
Construct: Trust in Organization					
Difference	0.3485	t Ratio	0.252771		
Std Err Dif	1.3787	DF	49		
Upper CL Dif	3.119	Prob > t	0.8015		
Lower CL Dif	-2.422	Prob > t	0.4008		
Confidence	0.95	Prob < t	0.5992		
Group	Number	Mean	Std Error	Lower 95%	Upper 95%
Control	18	0.5	1.109	-1.729	2.7286
Intervention	33	0.848485	0.819	-0.797	2.4944

Based on the results (Independent Sample $t = -.0538$, $df=36$, $p=.5939$) the null hypothesis is not rejected at both the .05 and 0.1 levels. There is no significant evidence that the intervention had any effect on increasing gain scores from pre-test to the *second post-test* of trust in organization among intervention participants.

Table 21: Employee Trust in Organization Post-Test 2 Results

Gain Score Anova Pre-Test to Post-Test 2					
Construct: Trust in Organization					
Difference	-0.6	t Ratio	-0.53793		
Std Err Dif	1.1154	DF	36		
Upper CL Dif	1.6621	Prob > t	0.5939		
Lower CL Dif	-2.8621	Prob > t	0.703		
Confidence	0.95	Prob < t	0.297		
Group	Number	Mean	Std Error	Lower 95%	Upper 95%
Control	18	0.5	0.80919	-1.141	2.1411
Intervention	20	-0.1	0.76766	-1.657	1.4569

Employee Adoption Readiness

Based on the results (Independent Sample $t = 2.442$, $df = 49$, $p = .0183$) the null hypothesis is rejected at both the 0.05 level and the 0.1 level. There is significant evidence at the 0.5 level that the intervention was effective at increasing gain scores from pre-test to *post-test 1* Adoption Readiness among intervention participants.

Table 22: Employee Adoption Readiness Post-Test 1 Results

Gain Score Anova Pre-Test to Post-Test 1					
Construct: Adoption Readiness					
Difference	1.26768	t Ratio	2.442005		
Std Err Dif	0.51911	DF	49		
Upper CL Dif	2.31087	Prob > t	0.0183		
Lower CL Dif	0.22448	Prob > t	0.0091		
Confidence	0.95	Prob < t	0.9909		
Group	Number	Mean	Std Error	Lower 95%	Upper 95%
Control	18	0.27778	0.41757	-0.5614	1.1169
Intervention	33	1.54545	0.3084	0.9257	2.1652

Based on the results (Independent Sample $t=.578$, $df=36$, $p=.566$) the null hypothesis is not rejected at both the .05 and 0.1 levels. There is no significant evidence that the intervention had any affect on increasing gain scores of Adoption Readiness from the pre-test to the *second post-test* among intervention participants.

Table 23: Employee Adoption Readiness Post-Test 2 Results

Gain Score Anova Pre-Test to Post-Test 2					
Construct: Adoption Readiness					
Difference	0.4722	t Ratio	0.578361		
Std Err Dif	0.8165	DF	36		
Upper CL Dif	2.1281	Prob > t	0.5666		
Lower CL Dif	-1.1837	Prob > t	0.2833		
Confidence	0.95	Prob < t	0.7167		
Group	Number	Mean	Std Error	Lower 95%	Upper 95%
Control	18	0.277778	0.59234	-0.9235	1.4791
Intervention	20	0.75	0.56194	-0.3897	1.8897

Worker Intervention Discussion

The worker intervention construct gain scores that were shown to increase among intervention group participants were self-efficacy, trust in technology and adoption readiness. Construct gain score differences not found to be significant were health knowledge, perceived risk, and trust in organization.

Worker Self-Efficacy Discussion

Self-efficacy gain scores for the worker intervention group were found significantly higher than those of the control group on the second post-test, which occurred three months after the initial pre-test, intervention, and initial post-test. The first post-test for self-efficacy was not found to be significant. This could be explained since the workers were only shown how to use vacuum sanders during the intervention and had limited hands-on training to provide a lot of experience

with the technology. The second post-test scores did show significant improvement that is in line with the HBM guidelines for using self-efficacy to enhance personal skills (Rosenstock 1988). The intervention targeted self-efficacy because skill training may be required to help people enhance self-efficacy before adopting a certain behavior. Performance accomplishments where the person has the ability to successfully try the skill or behavior and master the skill has been found to be the most effective method of obtaining self-efficacy (Rosenstock 1988). This finding is similar to those of an intervention to improve lead safety practices among painting contractors and their employees who were trained on-site and given the skills to improve their self-efficacy in implementing safe practices on the jobsite (Materna 2002). Workers in this lead safety study received educational training including technical assistance, focusing on hands-on demonstrations, participatory exercises and hands-on demonstrations of vacuum power tools. It was found that the workers in the lead safety study improved their skill and usage of ventilated tools and became more accurate in selecting appropriate respiratory protection methods. This study is similar to the DUSTI intervention in that workers gained self-efficacy with the vacuum sanders after the training and increased in their intent to adopt the new technology that can lead to implementation.

Worker Trust in Technology Discussion

Trust in technology gain scores for the worker intervention group were found to be significantly higher than those of the control group on the first post-test which immediately followed the intervention. The gain scores differences on the second post-test for trust in technology were not found to be significant. The gain in trust in technology scores on the first post-test were expected since efforts were made to enhance the individual's expectation that the technology will exhibit the elements of predictability, reliability and utility (Lippert 2005). The intervention showed the effectiveness of the technology and allowed the users to interact with the technology and see potential benefits of using the tool as found in previous studies where trust in technology was built in physicians accepting new technology when the perceived benefits could be seen and the tangible results of the technology are apparent to users (Yi et al. 2006).

The lack of significance in gain score differences for trust in technology on the second post-test for workers was unexpected. Possible explanations for this lack of gain could be related to the findings in the open ended responses from employers stating that while the vacuum sanding technology is a good idea and reduces dust, the quality of finishes could be diminished. A previous intervention dealing with implementing new working methods to reduce the knee strain in floor layers found that workers can be reluctant to accept changes in working methods because they will at least for a period decrease their work intensity and output. This study found that workers who did not implement the new practices immediately after the interventions did not tend to use them later and have not increased their trust in the new system (Jensen and Kofoed 2002). If the workers in the intervention were not able to use the sanders immediately after the

intervention in their work, it could explain the lack of increased gain scores for trust in technology.

Worker Adoption Readiness Discussion

Adoption readiness gain scores for the worker intervention group were found significant on the first post-test that immediately followed the intervention. The gain scores on the second post-test for adoption readiness were not found to be significant. The gain in trust in technology scores on the first post-test were expected because as in other interventions that have been successful at increasing adoption readiness, the elements of relative advantage, compatibility, complexity, triability, and observability of the DOI model were all incorporated into the design of the intervention (Rogers 2003). Other interventions successfully using these elements of the DOI to increase adoption readiness include using hydraulic ladder racks for mechanical contractors (Kramer 2009) and the intention of utility companies to adopt energy conservation interventions (Vollink 2002). The lack of significance in gain score differences for adoption readiness on the second post-test for workers was unexpected. Possible explanations for this lack of gain could be related to the findings relating to the concern over the quality of finish the vacuum sanders produce. An innovation must allow the adopter to execute actions that increase the organization's performance (Toole 1998). If workers did not perceive the technology to increase their performance upon gaining experience with the technology, their adoption readiness level could potentially be affected.

Worker Health Knowledge Discussion

Health Knowledge gain scores for the worker intervention group were not found to be significant on the first post-test which immediately followed the intervention or on the second post-test three months following the intervention. This lack of gain score increase was unexpected at the onset of the research. However, upon review of the data, it was noted that pre-test scores of health knowledge were already high, leaving little room for gain-score increase upon post-testing. Initial mean scores for health knowledge were (5.51) based on a 7-point scale. Post-test mean scores for the immediate post-test (6.24) and for the three month follow up post-test (6.3) were higher than the initial pre-test scores but overall gain scores were not found to be significant. The mean scores for health knowledge items shows there was some increase in health knowledge among some employees but with the mean scores being scoring high on a scale of 1-7, there was already a high level of health knowledge among workers in the drywall industry about the possible health effects drywall dust can pose. Results from other worksite health promotion activities have yielded promising yet modest health behavioral changes while evidence suggests that employees who participate in workplace health promotion interventions achieve positive health outcomes (Linnan 2001). Helping workers to become aware of the risks they are exposed to by increasing health knowledge, perceived susceptibility, perceived severity and helping them to break down any perceived barriers by teaching self-efficacy and allowing them to realize the

benefits of healthy behaviors can easily be adapted to work site situations and hazards (Conrad et al. 1996).

Worker Perceived Risks Discussion

Perceived risk to health gain scores for the worker intervention group were not found to be significant on the first post-test which immediately followed the intervention or on the second post-test three months following the intervention. This lack of gain score increase was unexpected at the onset of the research. However, upon review of the data, it was noted that pre test scores showed evidence of perceived risk from working around drywall dust was found to exist but not at a high level. The mean score for perceived risk on the initial pre-test was (5.23) based on a 7-point scale. Post-test mean scores for the immediate post-test (5.99) and for the three month follow up post-test (6.05) were higher than the initial pre-test scores but overall gain scores were not found to be significant. These scores reveal that there is some level of perceived risk but that the intervention failed to increase the health threat workers view working around drywall to be. The main elements that make up the perceived risk construct are: perceived susceptibility and perceived severity (Rosenstock 1960; Rosenstock 1988; Elder 1999). These elements are the major determining factors that cause people to adopt or continue practices that are meant to protect a person's safety and health. The first is the degree to which a person feels he or she is susceptible to a certain health problem or disease. The second is the severity the person believes that contracting the disease or health problem would have serious consequences to them (Rosenstock 1960).

Explanations for the lack of gain score increase could be that the intervention did not adequately communicate the severity of drywall dust risk. Also, the intervention might not have adequately addressed the worker susceptibility to disease from this dust. Another possible explanation is the delay between adoption and health benefits. This time lag may make perception of risk difficult in the immediate term. The consequence of not adopting the innovation on their health may never occur. Preventative innovations such as the one conducted in this research have been perceived as having low relative advantage as compared to other innovations that show immediate impact on health benefits or that are designed to create a profit (Rogers 2002).

Worker Trust in Organization Discussion

Trust in organization gain scores for the worker intervention group were not found to be significant on the first post-test which immediately followed the intervention or on the second post-test three months following the intervention. This lack of gain score increase was unexpected at the onset of the research. However, upon review of the data, it was noted that pre-test scores of trust in organization among participants, a level of trust in organization was found to exist. The mean score for organizational trust on the initial pre-test was (5.73) based on a 7-point scale. Post-test mean scores for the immediate post-test (5.92) and for the three month follow up post-test (5.76) were slightly higher than the initial pre-test scores but overall gain scores were not found to be significant. These scores reveal that there was some level of trust in organization already present and that the intervention failed to significantly increase the trust in organization of workers. The intervention focused on improving worker skills and ability to use

dust-control methods that has been found to increase trust in organizations. Employees who view themselves as having a high degree of ability and experience are more likely to place a higher degree of trust in the organization than those who do not view themselves as having the ability and experience in the company (Podsakoff et al. 1996). By working with employers and workers, the intervention tried to foster better communication, sharing in decision making and sharing of information with employees helps to build organizational trust (Gilbert and Tang 1998). The lack of gain score increase in the organizational trust construct indicated that the health and safety intervention had little if any impact on organizational trust or that there were deficiencies in the instrument measuring this construct. This finding is doesn't support the use of trust in organization as an integral component of increasing worker intent to adopt new technology.

Aim 4:

Small Employer Intervention Development, Implementation, Evaluation

Introduction

The design of the Small Firm intervention was guided by the constructs of the PtD ARM most relevant to the small firm owner stakeholder group of the construction industry: perceived risk to health, health knowledge, perceived usefulness, perceived ease of use, trust in technology. All of these antecedent constructs were expected to influence overall readiness to adopt the technological innovation.

Table 24: Small Firm Intervention Design Constructs

Intervention Theoretical Target Constructs		
Worker Intervention	Small Firm Intervention	Large Firm Intervention
Perceived Risk to Health (HBM)	Perceived Risk to Health (HBM)	Perceived Risk to Health (HBM)
Health Knowledge (HBM)	Health Knowledge (HBM)	Health Knowledge (HBM)
Trust in Organization (TAM)	Perceived Usefulness (TAM, DOI)	Perceived Usefulness (TAM, DOI)
Trust in Technology (TAM)	Perceived Ease of Use (DOI, TAM)	Perceived Ease of Use (DOI, TAM)
Adoption Readiness/Intent to Adopt (DOI, TAM)	Trust in Technology (TAM)	Trust in Technology (TAM)
Self-Efficacy (HBM)	Adoption Readiness/ Intent to Adopt (DOI, TAM)	Adoption Readiness/ Intent to Adopt (DOI, TAM)

Small firm owners were targeted because decisions to use new innovations is not usually up to the individual workers but are made by the managers of the company (Koebel 1999). The intervention consisted of a mixed informational and interactive training session with the owners of small drywall firms that included information about the material composition of drywall compound, the constituents that are present during drywall sanding operations, effects of illness related to drywall dust exposure, previous studies relating to worker exposure and health outcomes, disease trends in the drywall finishing industry, regulatory issues, and engineered dust control technologies and their impact on productivity and customer satisfaction. The workers and small firms received handouts at the end of the training (Appendix B) that provided basis for the materials covered. The training also included a hands-on demonstration of drywall finishing using vacuum sanders that allowed participants to gain familiarity with the dust-control technology. Small firm intervention participants received a vacuum sander to use in their company. Providing the sanders at no cost to the owners allowed them and their workers to try the technology at no investment risk and provided triability, a key element that can influence the diffusion of new innovations. As owners and workers were able to use the sander free of charge, it allowed them the opportunity to gain familiarity with the tool, increase their self efficacy, increase trust in the technology, and overcome potential barriers to adoption which can all be influential in the decision to adopt new technology.

The aim of the training session was to create a “technology champion” within the small firms. Technology champions are indispensable players in the diffusion of innovation process. These champions sponsor, protect and promote new products and methods and have the authority to negotiate and balance the opportunities and risks of using new technologies against the previous products or methods (Manseau and Shields 2005). Technology champions are highly enthusiastic and committed individuals who are willing to make special efforts and take risks to lead innovation processes in a company. Previous work by Keobel has shown that technology champions within companies can significantly improve the adoption of new technologies and work methods (Koebel 2008). Technology champions are willing to take risks associated with innovation. In a previous diffusion of innovation study, about 70% of construction firms surveyed were found to have a technology champion within their company who kept them aware of innovative product and processes (Koebel 2008). As a person finds out about a new product or process and takes a risk and begins to use it, they share their personal and subjective experiences with others which gradually give meaning to the innovation and help people to adopt the new ideas (Rogers 2004). The identification of a champion in small firms was used to help promote the use of vacuum sanders. Champions were identified through either through self-reporting or through peer identification.

Table 25: Employer Construct Item Measurements

Construct	Questions measuring construct
Health Knowledge	Exposure to drywall dust poses a potential health risk to workers
	Components of drywall dust can cause health problems.
Perceived Risk	Working in the drywall industry is a risk factor for certain illnesses
	My employees are susceptible to major health problems from exposure to drywall dust
	Serious health problems can result from working around drywall dust
Trust in Technology	When using vacuum sanders, workers are exposed to lower dust concentration levels than conventional block sanding
	I trust vacuum sanders.
Perceived Usefulness	Using vacuum sanders increases productivity
	Vacuum sanders are a good tool to use for sanding drywall
	Vacuum sanders save my company time
	Vacuum sanders produce quality drywall finishes
Perceived Ease of Use	It is convenient to use a vacuum sander
	My employees could effectively use vacuum sanders
	It will take a long time for my employees to learn to use vacuum sanders
	Vacuum sanders are too complex
	Vacuum sanders are easy to use
Adoption Readiness	I anticipate my company will use (or continue to use) drywall sanders in our work
	My company always tries to use vacuum sanders in as many cases/occasions as possible

The Small Firm intervention began with a member of the research team contacting drywall companies based on the recommendations of local drywall suppliers. The researchers obtained consent from the drywall companies recruited as volunteer participants who received the intervention. Participants were compensated in the amount of fifteen dollars an hour. The participants were assigned as either control group or intervention group participants and given a pretest as a basis for evaluation of the intervention. The control participants contact information was taken and attempts were made to contact participants again in three months to receive the posttest. Intervention participants were given the intervention immediately following the pretest and then received the posttest immediately following the intervention. Those participants with whom successful contact was made again after 3 months were given a final posttest.

The small firm interventions were held on the jobsite where the employees were working so that practical hands on experience could be demonstrated in the training and disruption of employer operations could be minimized. An authorized OSHA outreach trainer with experience in teaching construction safety topics administered the training sessions in this intervention. Interactive training was used as this method has been strongly associated with achieving desired changes in work practices (Goldenhar 2001). The implementation aimed to increase employer knowledge about working around drywall dust and how to control the hazard, decrease negative perceptions about the control methods and allowed them to see the tools in action to enhance trust in the technology. All employers received a certificate of training to acknowledge they have received health and safety training from an OSHA authorized trainer. The certificate aimed to enhance the credibility of the training and provided employers added training documentation that OSHA regulations require employers to keep. As part of the small-firm intervention, small firm owners were given a drywall sander free of charge for use within their company. This allowed the owners to use the tool free of investment risk and give them the ability to champion the technology in their firm by implementing the use on their projects among their workers.

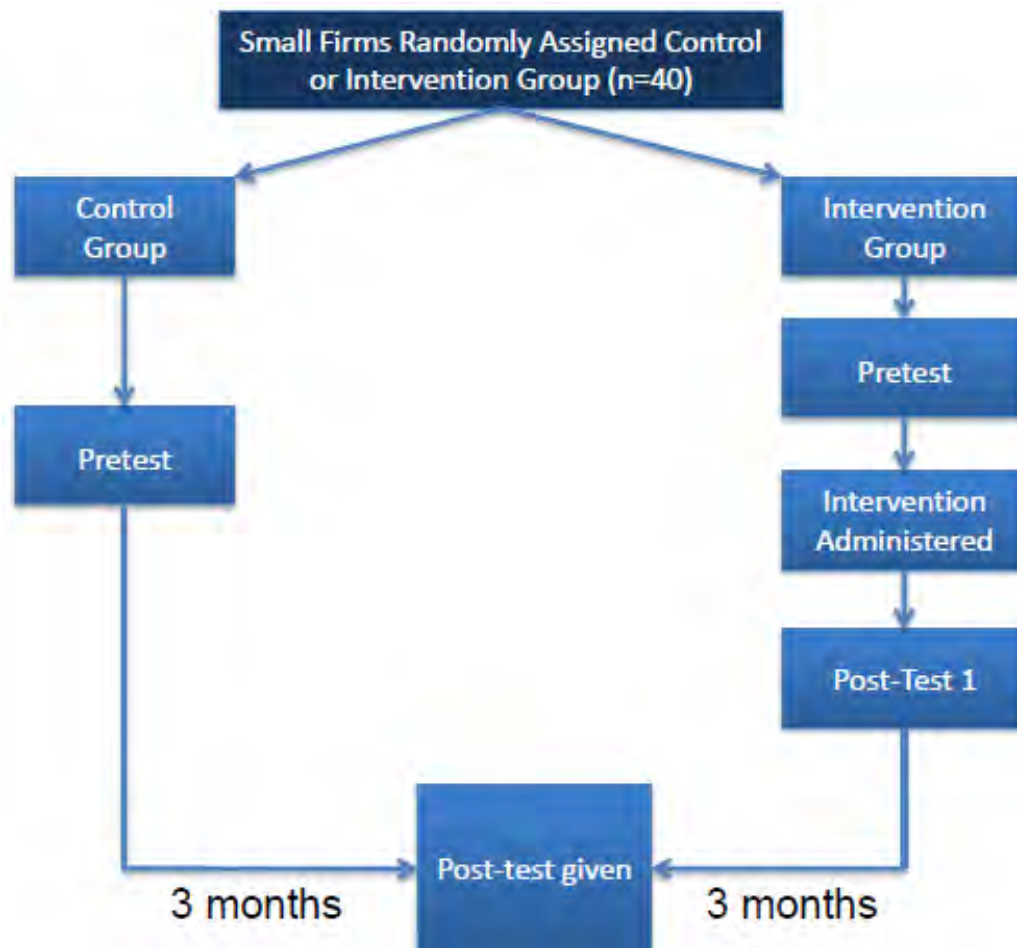


Figure 7. Small Firm Research Design

Small Firm Results

The following hypotheses were examined to determine intervention effectiveness.

Null Hypothesis 1= Post-test gain scores of **health knowledge** for small firm intervention participants will be no different than post-test scores in the small firm control group for post-test 1 and post-test 2.

Null Hypothesis 2= Post-test gain scores of **perceived risk** for small firm intervention participants will be no different than post-test scores in the small firm control group for post-test 1 and post-test 2.

Null Hypothesis 3= Post-test gain scores of **trust in technology** for small firm intervention participants will be no different than post-test scores in the small firm control group for post-test 1 and post-test 2.

Null Hypothesis 4= Post-test gain scores of **perceived usefulness (PU)** for small firm intervention participants will be no different than post-test scores in the small firm control group for post-test 1 and post-test 2.

Null Hypothesis 5= Post-test gain scores of **perceived ease of use (PEOU)** for small firm intervention participants will be no different than post-test scores in the small firm control group for post-test 1 and post-test 2.

Null Hypothesis 6= Post-test gain scores of **adoption readiness** for small firm intervention participants will be no different than post-test scores in the small firm control group for post-test 1 and post-test 2.

A summary of the small firm intervention evaluation based on a gain score analysis measuring each construct is shown in Table 32. Individual construct statistical results are reported in more detail in the sections that follow.

Table 26: Small Firm Intervention Results Summary

Small Firm Intervention Results Summary			
Construct Measured	Gain Score p value	Significant at .05	Significant at 0.1
Health Knowledge Post-Test 1	0.813	No	No
Health Knowledge Post-Test 2	0.733	No	No
Perceived Risk Post-Test 1	0.0012	Yes	Yes
Perceived Risk Post-Test 2	0.029	Yes	Yes
Trust in Technology Post-Test 1	0.038	Yes	Yes
Trust in Technology Post-Test 2	0.0462	Yes	Yes
Perceived Usefulness Post-Test 1	0.089	No	Yes
Perceived Usefulness Post-Test 2	0.063	No	Yes
Perceived Ease of Use Post-Test 1	0.578	No	No
Perceived Ease of Use Post-Test 2	0.0214	Yes	Yes
Adoption Readiness Post-Test 1	0.223	No	No
Adoption Readiness Post-Test 2	0.064	No	Yes

Small Firm Health Knowledge

Based on the results (Independent Sample $t = .239$, $df = 35$, $p = .813$) the null hypothesis is not rejected at both the .05 and 0.1 levels. There is no significant evidence that the intervention had any effect on increasing gain scores of health knowledge from pre-test to the *first post-test* among intervention participants.

Table 27: Small Firm Health Knowledge Post-Test 1 Results

Gain Score Anova Pre-Test to Post-Test 1					
Construct: Health Knowledge					
Difference	0.2176	t Ratio	0.238622		
Std Err Dif	0.9121	DF	35		
Upper CL Dif	2.0693	Prob > t	0.8128		
Lower CL Dif	-1.634	Prob > t	0.4064		
Confidence	0.95	Prob < t	0.5936		
Group	Number	Mean	Std Error	Lower 95%	Upper 95%
Control	17	0.88235	0.67059	-0.479	2.2437
Intervention	20	1.1	0.61825	-0.1551	2.3551

Based on the results (Independent Sample $t = .344$, $df = 32$, $p = .733$) the null hypothesis is not rejected at both the .05 and 0.1 levels. There is no significant evidence that the intervention had any effect on increasing gain scores of health knowledge from the pre-test to the *second post-test* among intervention participants.

Table 28: Small Firm Health Knowledge Post-Test 2 Results

Gain Score Anova Pre-Test to Post-Test 2					
Construct: Health Knowledge					
Difference	0.2941	t Ratio	0.34452		
Std Err Dif	0.8537	DF	32		
Upper CL Dif	2.0331	Prob > t	0.7327		
Lower CL Dif	-1.4448	Prob > t	0.3664		
Confidence	0.95	Prob < t	0.6336		
Group	Number	Mean	Std Error	Lower 95%	Upper 95%
Control	17	0.88235	0.60366	-0.3473	2.112
Intervention	17	1.17647	0.60366	-0.0531	2.4061

Small Firm Perceived Risk to Health

Based on the results (Independent Sample $t = 3.51$, $df = 35$, $p = .0012$) the null hypothesis is rejected at both the .05 and 0.1 levels. There is significant evidence that the intervention had effect on increasing gain scores of perceived risk to health from pre-test to the *first post-test* among intervention participants.

Table 29: Small Firm Perceived Risk Post-Test 1 Results

Gain Score Anova Pre-Test to Post-Test 1					
Construct: Perceived Risk					
Difference	3.37059	t Ratio	3.51323		
Std Err Dif	0.9594	DF	35		
Upper CL Dif	5.31827	Prob > t	0.0012		
Lower CL Dif	1.42291	Prob > t	0.0006		
Confidence	0.95	Prob < t	0.9994		
Group	Number	Mean	Std Error	Lower 95%	Upper 95%
Control	17	-0.4706	0.70536	-1.903	0.9614
Intervention	20	2.9	0.65031	1.58	4.2202

Based on the results (Independent Sample $t = 2.28$, $df = 32$, $p = .0296$) the null hypothesis is rejected at both the .05 and 0.1 levels. There is significant evidence that the intervention had an effect on increasing gain scores of perceived risk from the pre-test to the *second post-test* among intervention participants.

Table 30: Small Firm Perceived Risk Post-Test 2 Results

Gain Score Anova Pre-Test to Post-Test 2			
Construct: Perceived Risk			
Difference	2.47059	t Ratio	2.276933
Std Err Dif	1.08505	DF	32
Upper CL Dif	4.68076	Prob > t	0.0296

Lower CL Dif	0.26041	Prob > t	0.0148		
Confidence	0.95	Prob < t	0.9852		
Group	Number	Mean	Std Error	Lower 95%	Upper 95%
Control	17	-0.4706	0.76725	-2.033	1.0922
Intervention	17	2	0.76725	0.437	3.5628

Small Firm Trust in Technology

Based on the results (Independent Sample $t = 2.16$, $df = 35$, $p = .0379$) the null hypothesis is rejected at both the .05 and 0.1 levels. There is significant evidence that the intervention had affect on increasing gain scores of trust in technology from pre-test to the *first post-test* among intervention participants.

Table 31: Small Firm Trust in Technology Post-Test 1 Results

Gain Score Anova Pre-Test to Post-Test 1					
Construct: Trust in Technology					
Difference	1.47647	t Ratio	2.157164		
Std Err Dif	0.68445	DF	35		
Upper CL Dif	2.86598	Prob > t	0.0379		
Lower CL Dif	0.08696	Prob > t	0.019		
Confidence	0.95	Prob < t	0.981		
Group	Number	Mean	Std Error	Lower 95%	Upper 95%
Control	17	-0.1765	0.50322	-1.198	0.8451
Intervention	20	1.3	0.46394	0.358	2.2419

Based on the results (Independent Sample $t = 2.0715$, $df = 33$, $p = .0462$) the null hypothesis is rejected at both the .05 and 0.1 levels. There is significant evidence that the intervention had an affect on increasing gain scores of trust in technology from the pre-test to the *second post-test* among intervention participants.

Table 32: Small Firm Trust in Technology Post-Test 2 Results

Gain Score Anova Pre-Test to Post-Test 2			
Construct: Trust in Technology			
Difference	1.56536	t Ratio	2.071511

Std Err Dif	0.75566	DF	33		
Upper CL Dif	3.10276	Prob > t	0.0462		
Lower CL Dif	0.02796	Prob > t	0.0231		
Confidence	0.95	Prob < t	0.9769		
Group	Number	Mean	Std Error	Lower 95%	Upper 95%
Control	17	-0.1765	0.54191	-1.279	0.9261
Intervention	18	1.3889	0.52664	0.317	2.4604

Small Firm Perceived Usefulness

Based on the results (Independent Sample $t = 1.74$, $df = 35$, $p = .089$) the null hypothesis is not rejected at the .05 and rejected at the 0.1 level. There is significant evidence at the 0.1 level that the intervention had an affect on increasing gain scores of perceived usefulness from pre-test to the *first post-test* among intervention participants.

Table 33: Small Firm Perceived Usefulness Post-Test 1 Results

Gain Score Anova Pre-Test to Post-Test 1					
Construct: Perceived Usefulness					
Difference	3.1147	t Ratio	1.74421		
Std Err Dif	1.7857	DF	35		
Upper CL Dif	6.74	Prob > t	0.0899		
Lower CL Dif	-0.5105	Prob > t	0.045		
Confidence	0.95	Prob < t	0.955		
Group	Number	Mean	Std Error	Lower 95%	Upper 95%
Control	17	1.23529	1.3129	-1.43	3.9006
Intervention	20	4.35	1.2104	1.893	6.8073

Based on the results (Independent Sample $t = 1.93$, $df = 33$, $p = .0626$) the null hypothesis is not rejected at the .05 and rejected at the 0.1 level. There is significant evidence at the 0.1 level that the intervention had an affect on increasing gain scores of perceived usefulness from pre-test to the *second post-test* among intervention participants.

Table 34: Small Firm Perceived Usefulness Post-Test 2 Results

Gain Score Anova Pre-Test to Post-Test 2					
Construct: Perceived Usefulness					

Difference	1.9444	t Ratio	1.276427		
Std Err Dif	1.5233	DF	36		
Upper CL Dif	5.0339	Prob > t	0.21		
Lower CL Dif	-1.1451	Prob > t	0.105		
Confidence	0.95	Prob < t	0.895		
Group	Number	Mean	Std Error	Lower 95%	Upper 95%
Control	18	0.55556	1.1052	-1.686	2.7969
Intervention	20	2.5	1.0484	0.374	4.6263

Small Firm Perceived Ease of Use

Based on the results (Independent Sample $t = 1.96$, $df = 35$, $p = .578$) the null hypothesis is not rejected at the .05 and rejected at the 0.1 level. There is significant evidence at the 0.1 level that the intervention had an affect on increasing gain scores of perceived ease of use from pre-test to the *first post-test* among intervention participants.

Table 35: Small Firm Perceived Ease of Use Post-Test 1 Results

Gain Score Anova Pre-Test to Post-Test 1					
Construct: Perceived Ease of Use					
Difference	3.8203	t Ratio	1.926946		
Std Err Dif	1.9825	DF	33		
Upper CL Dif	7.8538	Prob > t	0.0626		
Lower CL Dif	-0.2133	Prob > t	0.0313		
Confidence	0.95	Prob < t	0.9687		
Group	Number	Mean	Std Error	Lower 95%	Upper 95%
Control	17	1.23529	1.4218	-1.657	4.1279
Intervention	18	5.05556	1.3817	2.244	7.8666

Based on the results (Independent Sample $t = 2.419$, $df = 32$, $p = .0214$) the null hypothesis is rejected at both the .05 and 0.1 levels. There is significant evidence that the intervention had an

affect on increasing gain scores of perceived ease of use from the pre-test to the *second post-test* among intervention participants.

Table 36: Small Firm Perceived Ease of Use Post-Test 2 Results

Gain Score Anova Pre-Test to Post-Test 2					
Construct: Perceived Ease of Use					
Difference	3.8088	t Ratio	1.9615		
Std Err Dif	1.9418	DF	35		
Upper CL Dif	7.7509	Prob > t	0.0578		
Lower CL Dif	-0.1332	Prob > t	0.0289		
Confidence	0.95	Prob < t	0.9711		
Group	Number	Mean	Std Error	Lower 95%	Upper 95%
Control	17	-1.0588	1.4276	-3.957	1.8394
Intervention	20	2.75	1.3162	0.078	5.4221

Small Firm Adoption Readiness

Based on the results (Independent Sample $t = 1.24$, $df = 35$, $p = .223$) the null hypothesis is not rejected at both the .05 and 0.1 levels. There is no significant evidence that the intervention had any affect on increasing gain scores of adoption readiness from pre-test to the *first post-test* among intervention participants.

Table 37: Small Firm Adoption Readiness Post-Test 1 Results

Gain Score Anova Pre-Test to Post-Test 1					
Construct: Adoption Readiness					
Difference	5.41176	t Ratio	2.419482		
Std Err Dif	2.23674	DF	32		
Upper CL Dif	9.96786	Prob > t	0.0214		
Lower CL Dif	0.85566	Prob > t	0.0107		
Confidence	0.95	Prob < t	0.9893		
Group	Number	Mean	Std Error	Lower 95%	Upper 95%

Control	17	-1.0588	1.5816	-4.28	2.1628
Intervention	17	4.3529	1.5816	1.131	7.5746

Based on the results (Independent Sample $t=1.91$, $df=32$, $p=.0643$) the null hypothesis is not rejected at the .05 and rejected at the 0.1 level. There is significant evidence at the .1 level that the intervention had an affect on increasing gain scores of adoption readiness from pre-test to the *second post-test* among intervention participants.

Table 38: Small Firm Adoption Readiness Post-Test 2 Results

Gain Score Anova Pre-Test to Post-Test 2					
Construct: Adoption Readiness					
Difference	0.9235	t Ratio	1.240462		
Std Err Dif	0.7445	DF	35		
Upper CL Dif	2.435	Prob > t	0.2231		
Lower CL Dif	-0.5879	Prob > t	0.1115		
Confidence	0.95	Prob < t	0.8885		
Group	Number	Mean	Std Error	Lower 95%	Upper 95%
Control	17	0.17647	0.54737	-0.9348	1.2877
Intervention	20	1.1	0.50465	0.0755	2.1245

Small-Firm Intervention

The small firm intervention construct gain scores that were shown to increase among intervention group participants were perceived risk, trust in technology, perceived usefulness, perceived ease of use, trust in technology and adoption readiness. The construct gain scores not found to be significant in the small firm intervention were health knowledge.

Small Firm Perceived Risk Discussion

Perceived Risk gain scores for the small firm intervention group were found significant on both the immediate post-test following the intervention as well as on the second post-test which occurred three months after the initial pre-test, intervention, and initial post-test. This outcome was expected at the outset of this research and is consistent with past interventions using this

construct of the HBM for increasing the perceived risk to health of participants. As small firms learned about the severity and susceptibility of their employees to health related problems associated with drywall dust exposure, their level of perceived risk increased similar to that of participants in other HBM interventions outlined in section 2.6 of this dissertation. Intervention examples discovered through the literature review which also used the HBM to increase participant's perceived risk include interventions to reduce smoking, interventions to increase breast cancer screening, increased nutrition at worksites, increase in colorectal cancer screenings, increased diabetes awareness and prevention, increased vaccination participation and various other health related concerns (Bastani 1995; Conrad et al. 1996; Vernon 1997; Aoun et al. 2002; Abood 2003; Dempsey 2006). This model focuses on perceptions, beliefs and other personal characteristics that influence whether a person feels at risk for a certain health problem and whether they position themselves to change certain health behaviors, health practices and/or to utilize health care services (Lux 1994). The DUSTI interventions presented health information to participants aimed at increasing their awareness of potential health issues. Attention was given to how accepting the PtD solutions could reduce their health risks and that they were in position to change their behavior with their choice of tools. Open-ended responses of contractors noted that health related days away from work, potential health problems, and insurance premium increases due to worker's compensation claims were a risk for their company and that there was a need to control employee exposure.

Small Firm Trust in Technology Discussion

Trust in technology gain scores for the small firm intervention group were found significant on both the immediate post-test following the intervention as well as on the second post-test which occurred three months after the initial pre-test, intervention, and initial post-test. This outcome was expected at the outset of this research and is consistent with past interventions using this construct of trust in technology to increase intent to use new technology. In order for changes in work procedures and practices in relation to technology acceptance to take place, trust must be a fundamental part of the organizational culture if the change is to be sustainable and adopted effectively (Podsakoff et al. 1996). Trust in technology research has been conducted in various fields including ecommerce, online marketplaces, information systems, medical technology and food science (Eiser 2002; Misiolek 2002; Yee 2005; Li et al. 2008; Montague et al. 2009). By increasing the small firm owner's knowledge of dust-control technology, their trust in the technology improved. This strategy was consistent with the intent of using the trust in technology construct to show that the more someone understands how something works, the more likely they are to put their trust in it (Dzindolet et al. 2003). Better operator knowledge of how a technology works will result in more appropriate use of technology (Parasuraman and Riley 1997).

Small Firm Perceived Usefulness Discussion

Perceived usefulness (PU) gain scores for the small firm intervention group were found significant on both the immediate post-test following the intervention as well as on the second post-test which occurred three months after the initial pre-test, intervention, and initial post-test. This outcome was expected at the outset of this research and is consistent with past interventions using the construct of PU combined with the PEOU construct of the TAM to increase PU. By showing the small firm owners how the tool worked and the advantages that using the tool provided to their firm, it can be assumed that the intervention demonstrated perceived usefulness to the firm owners and, thus, gain scores increased. This is consistent with interventions using this construct of the TAM including introducing new computer management systems in manufacturing firms (cite), increasing physician's decisions to adopt telemedicine and introducing a new interactive online help desk system (Hu 1999; Venkatesh 2000b, 2000c).

Small Firm Perceived Ease of Use Discussion

Perceived ease of use (PEOU) gain scores for the small firm intervention group were found significant on the second post-test which occurred three months after the initial pre-test, intervention, and initial post-test. The first post-test gain scores for PEOU was not found to be significant. This could be expected since the small firms were shown how to use the vacuum sanders during the intervention and had limited hands-on training to provide a lot of experience with the technology. The second post-test scores did show significant improvement that is in line with the TAM guidelines for using PEOU to enhance personal skills. This is consistent with interventions combining this construct of the TAM with the construct of PU. Interventions including introducing new computer management systems in manufacturing firms, increasing physician's decisions to adopt telemedicine and introducing a new interactive online help desk system have successfully used these constructs to also improve PEOU (Hu 1999; Venkatesh 2000b, 2000c). As companies were given the tool for use, they were able to become familiar with the technology and as experience is gained, PEOU is increased. The construct of self-efficacy has also been compared to PEOU in that a persons' perception of efficacy with a technology can influence their view on the ease of use the technology offers (Venkatesh 2000c; Yi et al. 2006).

Small Firm Adoption Readiness Discussion

Adoption readiness gain scores for the small firm intervention group were found significant on the second post-test which occurred three months after the initial pre-test, intervention, and initial post-test. The first post-test gain scores for adoption readiness were not found to be significant. This result was unexpected because as in other interventions that have been successful at increasing adoption readiness, the elements of relative advantage, compatibility, complexity, triability, and observability of the DOI model were all incorporated into the design of the intervention (Rogers 2003). The adoption readiness of firm owners might have not shown immediate impact due to the technology being new to them and they had yet to implement the tool to determine if the technology did follow the elements of the DOI model.

The significance of the second post-test gain scores was expected since small firms had time to implement the technology and use it on a trial basis to see if it provided relative advantage, was compatible with their work practices, wasn't too complex, had the opportunity to try the technology and were able to observe the tool in use. The increase in adoption readiness is consistent with other interventions successfully using these elements of the DOI to increase adoption readiness include using hydraulic ladder racks for mechanical contractors (Kramer 2009) and the intention of utility companies to adopt energy conservation interventions (Vollink 2002). The study using hydraulic racks was similar to the DUSTI study since it provided mechanical contractors the ladder racks to use free of charge which enhanced the element of triability and also provided training on the relative advantages, compatibility, and complexity of the ladder racks. The intentions of utility companies study focused on the DOI elements relative advantage and compatibility with the existing work practices to increase adoption readiness.

Small Firm Health Knowledge Discussion

Health knowledge gain scores for the small firm intervention group were not found to be significant on the first post-test which immediately followed the intervention or on the second post-test three months following the intervention. While the lack of gain score increase was unexpected at the onset of the research, upon review of the initial mean scores of health knowledge among participants, the level of health knowledge about working around drywall dust and the effects it can have on health was evident among small firms. Another factor that could be present is that firm owners could be hesitant in reporting health knowledge that could expose them to liability. Initial mean scores for health knowledge were (5.26) based on a 7-point scale. Post-test mean scores for the immediate post-test (5.69) and for the three month follow up post-test (6.06) were higher than the initial pre-test scores but overall gain scores were not found to be significant. The mean scores for health knowledge items shows there was some increase in health knowledge among some small firms, but with the mean scores being scored on a scale of 1-7, there was already a level of health knowledge among small firms in the drywall industry about the possible health effects drywall dust can pose. This was also evident in the open-ended responses from many of the contractors stating that health risks or health problems are a potential problem when working around drywall dust. Helping small firms to become aware of the risks they are exposed to by increasing health knowledge, perceived susceptibility, perceived severity and helping them to break down any perceived barriers by teaching self-efficacy and allowing them to realize the benefits of healthy behaviors can easily be adapted to work site situations and hazards (Conrad et al. 1996).

Aim 5:

Large Employer Intervention Development, Implementation, Evaluation

INTRODUCTION

The design of the Large Firm intervention included the PtD ARM constructs of relevance to large firm purchasing decision makers: perceived risk to health, health knowledge, perceived usefulness, perceived ease of use, trust in technology. All of which is expected to influence the overall readiness to adopt the PtD innovation.

Table 39: Large Firm Intervention Design Constructs

Intervention Theoretical Target Constructs		
Worker Intervention	Small Firm Intervention	Large Firm Intervention
Perceived Risk to Health (HBM)	Perceived Risk to Health (HBM)	Perceived Risk to Health (HBM)
Health Knowledge (HBM)	Health Knowledge (HBM)	Health Knowledge (HBM)
Trust in Organization (TAM)	Perceived Usefulness (TAM, DOI)	Perceived Usefulness (TAM, DOI)
Trust in Technology (TAM)	Perceived Ease of Use (DOI, TAM)	Perceived Ease of Use (DOI, TAM)
Adoption Readiness/Intent to Adopt (DOI, TAM)	Trust in Technology (TAM)	Trust in Technology (TAM)
Self-Efficacy (HBM)	Adoption Readiness/ Intent to Adopt (DOI, TAM)	Adoption Readiness/ Intent to Adopt (DOI, TAM)

The intervention for large firms was aimed at improving constructs that were identified as barriers to adoption of dust control tools and methods in previous studies by Young-Corbett (Young-Corbett and Nussbaum 2009b). The specific constructs that were targeted were: perceived risk to worker health resulting from dust exposure, health knowledge about the constituents contained in drywall dust and specific effects associated with drywall dust exposure, trust in technology, perceived usefulness, perceived ease of use, and adoption readiness of firms.

Purchasing departments play a large role in the adoption of new products and methods in large companies and are responsible for the decisions made and innovative risks taken (Koebel 2008). Purchasing agents must be convinced of a product's benefits and that manufacturers will support their products. Understanding products and processes and the potential benefits that could be realized through the use of new innovations could help purchasing agents make informed decisions about adopting safety and health innovations.

A web site was developed as part of the large firm intervention. The web site was structured to provide information on about drywall worker health and safety in regards to dust control as well as demonstrate the successful use of vacuum sanders. The information on the web site contained

findings from previous studies on drywall dust and the health effects it has on workers as well as regulatory drivers such as OSHA regulations and network effects such as insurance premiums that could influence the decision makers' decision to adopt. Included on the site were video clips showing the performance of the vacuum sander compared to the use of conventional sanding methods. The video demonstrated the time difference between the two methods in effort to demonstrate the productivity gains and health benefits that can be realized by using the vacuum sander. Screen shots from the website can be found in the following pages.



Begin

A project by the Virginia Tech [Occupational & Construction Hazard Reduction Engineering Lab](#)

This project is sponsored by [The National Institute for Occupational Safety And Health \(NIOSH\)](#).



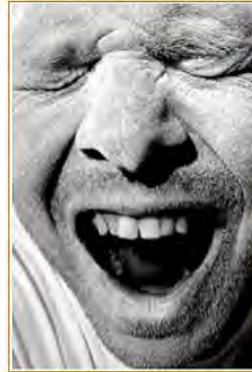
Review of Procedures

- Take online Survey # 1.
- Review website contents.
- Take online follow-up survey.
- \$25.00 Home Depot gift card will be emailed to you upon completion of the follow-up survey.
- In 3 months time you will be asked to take the survey again and will receive another \$25.00 Home Depot gift card email upon completion of the survey.

Next >

Health Hazard - Drywall Dust

- Construction workers involved in the sanding of drywall joint compound are often exposed to high concentrations of dust that can contain respirable silica.
- The components of drywall joint compound includes: talc, calcite, mica, gypsum and silica. Some of these components have been associated with varying degrees of eye, nose, throat and respiratory tract irritation.
- Over time, breathing the dust from drywall joint compounds may cause persistent throat and airway irritation, coughing, phlegm production and breathing difficulties similar to asthma.
- Smokers and workers with sinus or respiratory conditions may risk even worse health problems. When silica is present, workers may also face an increased risk of silicosis and lung cancer.
- Studies have shown that drywall workers are at an increased risk of developing chronic respiratory disease.
- Recent studies conducted by the National Institute for Occupational Safety and Health (NIOSH) have found that drywall sanders were exposed to as much as 10 times to permissible exposure limit (PEL) of 15mg/m³ for total dust set by the Occupational Safety and Health Administration (OSHA). The OSHA PEL for respirable dust (5mg/m³), the very small particles that can go deep into the lungs, was also exceeded.



NEXT >

Dust-Control Methods

Methods of finishing drywall have been developed that control dust exposures of workers and have been found to be effective at reducing the concentrations of dust to levels below the permissible limits as prescribed by OSHA. These methods and materials that have been found to reduce the dust levels during sanding operations when properly used are not widely used in the drywall industry for various reasons. Using dust-control methods can reduce the risk of illness and disease caused by exposure to drywall joint compound dust exposure. The following dust-control methods have been recommended by NIOSH to reduce worker exposure to dust:

- Wet Sanding
- Vacuum Sanding
- Low Dust Joint Compound
- PPE

NEXT >

Dust-Control Methods

Manufacturer's Recommendations: Wet Sanding

Drywall joint compound manufacturers recognize that workers might be exposed to too much dust during drywall sanding. NIOSH studied five manufacturer's material safety data sheets (MSDS's) that warned workers to avoid generating dust and to use respiratory protection when dry sanding. Four of the MSDSs told construction workers to use wet sanding whenever possible, and the fifth said to cut dust exposures "by ventilation." However, these guidelines are seldom followed in actual work practice. Wet sanding is generally avoided because of concerns of drying time and finish texture. When respiratory protection is used, it is often used incorrectly with little thought to training, proper selection, or fit. Respiratory protection for drywall dust needs to meet or exceed the NIOSH approved type N95 respirator.

NEXT >

Vacuum Sanders

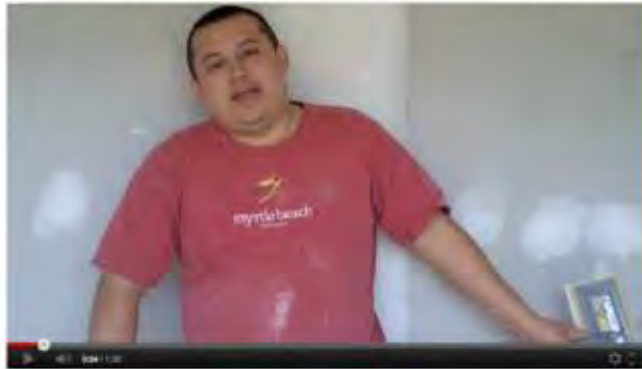
- Several light-weight vacuum sanding systems are now sold to control employee dust exposures when sanding joint compound. These systems use portable vacuums to capture and remove the dust before the employee is exposed to it. NIOSH conducted a study and found that the 5 commercially available vacuum sanders they tested successfully reduced dust exposures by 80- 97%. Four of the five tested cut exposures by nearly 95%. If these engineered controls had reduced total dust exposures by just 90%, the dust exposures in the NIOSH study described earlier would have remained below the OSHA PEL.
- In addition to lower exposures, vacuum systems can help the sander, subcontractor, general contractor, and building owner in other ways. The dramatic reduction in airborne dust exposures results in a much cleaner work area during and after sanding.
- For workers, the clean working environment is more comfortable; less irritating to eyes, nose, and throat; and less likely to require respiratory protection.
- For subcontractors, a comfortable worker is likely to be more productive, be absent less often, and require fewer breaks for "fresh air." Other cost savings will result from a cleaner environment that reduces dirt, and cleanup time.



NEXT >

Benefits of Vacuum Sanders

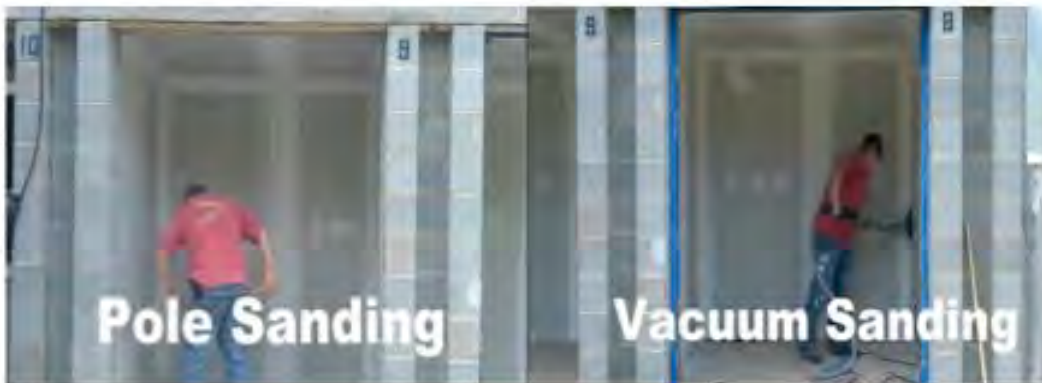
Edwin Gomez a drywall contractor in Virginia discusses the benefits of using vacuum sanders.



NEXT >

Benefits of Vacuum Sanders - Productivity

Vacuum sanders save your company time. A group of student researchers at Virginia Tech University conducted a Time and Motion Study Analysis comparing vacuum sanding and pole sanding and found that along with significant reductions in dust exposure, the powered vacuum sander increase productivity by 27%. The physical effort required by workers was reduced when measuring fatigue factors and and finish quality was comparable to hand or pole sanding when reviewed by an experienced drywall finisher.



NEXT >

Misuse of Powered Vacuum Sanders

Researchers have found that drywall finishers sometimes use creative disablement when using vacuum sanders and disable the safety features that are designed to control dust. Workers who use the vacuum sanders improperly and without the vacuum can cause greater health hazard exposures. The vacuum should always be connected when using power drywall sanders.



NEXT >

A Dust-Control Usage Strategic Technology Intervention

Low-Dust Drywall Compounds

Unlike traditional joint compounds, the fine dust particles in low-dust compounds bind together to form large particles when sanded. These larger particles quickly fall to the floor, reducing the potential exposure to airborne dust and silica. If sanding is brief and intermittent, this may reduce exposures enough that a respiratory protection program isn't required. However, continuous use may exceed the OSHA permissible PEL, even with the use of low-dust joint compounds. Manufacturers state that airborne dust is reduced by 70% when compared to sanding standard compounds.

- <http://www.downwithdust.com/faqs.php>
- <http://www.nationalgypsum.com/>



NEXT >

Personal Protective Equipment (PPE)

Respiratory Protection - OSHA requires that employees exposed to dust concentrations higher than the Permissible Exposure Limit to wear Filtering Facepiece Respirators (Dust masks). Dust masks prevent the inhalation of airborne dust. Dust mask training is required for anyone who wears a dust mask. Dust masks will leak if they are not worn properly. Dust masks do not filter out chemical vapors and are not adequate for high concentrations of dust. NIOSH Type 95 or higher Dust Masks are required for exposure to concentrations above the PEL. Type 95 masks filter out 95% of dust particles. N99 or N100 masks are recommended for dangerous dusts such as asbestos or silica. PPE is a last line of defense and OSHA would prefer that prevention of hazards through the design of tools and materials be used in lieu of PPE. Designing preventative measures into tools and materials takes away the decision employees make in when and how to use PPE. If PPE is required:

- Employers must train employees on proper usage of masks and provide fit testing and provide the masks for their employees.
- Dust Masks must fit properly to prevent leaks around the edges. Fit testing must be done before first wearing a dust mask. Beards do not allow a good fit when wearing a dust mask.
- Dust masks cannot be cleaned or repaired if soiled or damaged.
- Replace dust mask if breathing becomes difficult or if the mask is torn.
- Dispose of dust masks at the end of the day or shift.
- If you notice an odor, find dust inside the mask, or think your mask leaks, notify your supervisor.
- Store masks when not being used in a sealed container that will prevent dust from getting on inside of the mask.

NEXT >

A Dust-Control Usage Strategic Technology Intervention

Begin Survey

Having completed the Dust-Control Usage Strategic Technology Intervention, you will now be asked to complete the survey again.

NEXT >

Prior to the development of the web site, information about quality and productivity was generated through a work analysis study performed by graduate students at Virginia Tech. This work-study incorporated students trained drywall finishers who performed identical sanding tasks with a pole hand sander and again with a vacuum sander. The sanding sessions were recorded and analysis was performed to obtain data about the task cycle times and efficiency. Sanding area square footage completed in a given amount of time was measured to determine productivity of the workers. The results of the sanding sessions were evaluated for quality by professional drywall finishers. The results of these sanding sessions were included on the web site.

Large Firm Intervention Implementation

The Large Firm intervention began with contacting members of the national drywall trade organizations including Finishing Contractors Association (FCA) and Association of the Wall and Ceiling Industries (AWCI) and large drywall contracts referred by general contractors around the nation. Members of the research team made telephone contact with key purchasing decision makers in the large companies. In the telephone contact, consent to participate was obtained along with the participant's contact information followed by a pretest that was administered through online media to all participants. Control group participants were emailed a \$25 Home Depot gift card as compensation for their participation. Following the telephone contact, a follow-up email was sent to the purchasing decision maker, which contained a link to the intervention web site. Participants were asked to login using future contact information, take the pretest and then view the website content and then take a posttest after viewing the website. For the group that received the intervention, a short informational website session provided information about the availability and benefits of vacuum sanders and other dust control technologies. Information was also provided on health risks associated with drywall dust as well as evidence of work quality and productivity. Three months following the submission of the initial posttest, reminder emails were sent to participants with a link to the second posttest. Participants in the large firm intervention were compensated in the form of \$25 Home Depot gift

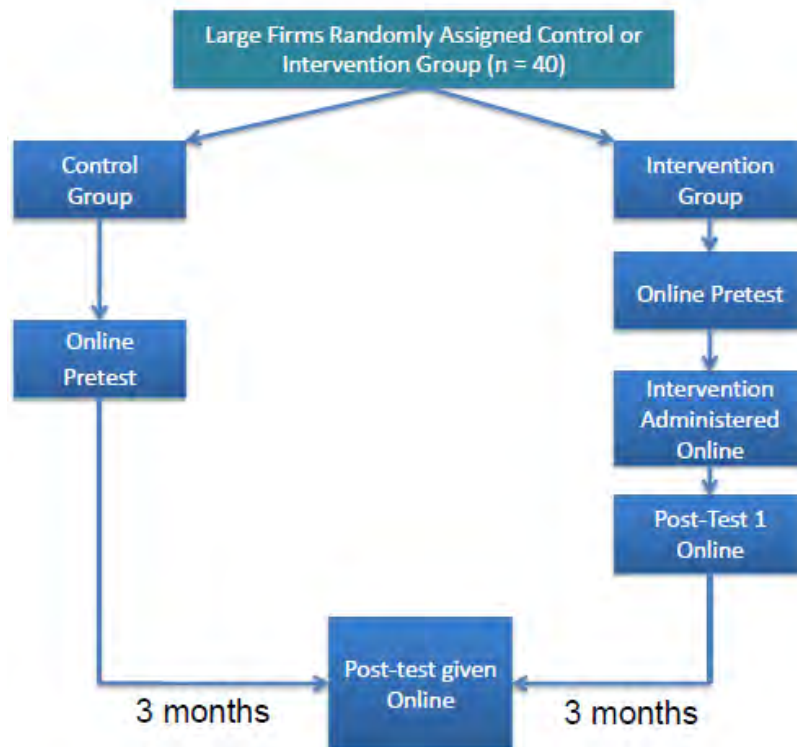


Figure 8. Large Firm Research Design

Analysis

Results of the scaled survey items that were grouped by theoretical construct and measured for each round. Post-test data was collected three months following the initial pre-test and first intervention post-test. A gain score analysis of variance, using an independent sample t-test (one way ANOVA) of the mean gain scores for each construct was used to test for differences in control and intervention groups for the post-test immediately following the intervention to see if the intervention had any immediate effect and again for the second post-test to see if the intervention had any lasting effect. All statistical analysis were performed using JMP ® 9.0.0 (SAS Institute Inc., Cary, NC).

The open-ended survey questions for small and large firm employers were analyzed using content analysis procedures. The researcher for each open-ended response category established codes for responses. These codes were then used to assign responses by independent coders who had been trained by the researcher on the particular coding definitions and process.

Large Firm Results

The following hypotheses were examined to determine intervention effectiveness.

Null Hypothesis 1= Post-test gain scores of **health knowledge** for large firm intervention participants will be no different than post-test scores in the large firm control group for post-test 1 and post-test 2.

Null Hypothesis 2= Post-test gain scores of **perceived risk** for large firm intervention participants will be no different than post-test scores in the large firm control group for post-test 1 and post-test 2.

Null Hypothesis 3= Post-test gain scores of **trust in technology** for large firm intervention participants will be no different than post-test scores in the large firm control group for post-test 1 and post-test 2.

Null Hypothesis 4= Post-test gain scores of **perceived usefulness (PU)** for large firm intervention participants will be no different than post-test scores in the large firm control group for post-test 1 and post-test 2.

Null Hypothesis 5= Post-test gain scores of **perceived ease of use (PEOU)** for large firm intervention participants will be no different than post-test scores in the large firm control group for post-test 1 and post-test 2.

Null Hypothesis 6= Post-test gain scores of **adoption readiness** for large firm intervention participants will be no different than post-test scores in the large firm control group for post-test 1 and post-test 2.

A summary of the small firm intervention evaluation based on a gain score analysis measuring each construct is shown in Table 45. Individual construct statistical results are reported in more detail in the sections that follow.

Table 40: Large Firm Results Summary

Large Firm Intervention Results Summary			
Construct Measured	Gain Score p value	Significant at .05	Significant at 0.1
Health Knowledge Post-Test 1	0.584	No	No
Health Knowledge Post-Test 2	0.171	No	No

Perceived Risk Post-Test 1	0.114	No	No
Perceived Risk Post-Test 2	0.06	No	Yes
Trust in Technology Post-Test 1	0.569	No	No
Trust in Technology Post-Test 2	0.209	No	No
Perceived Usefulness Post-Test 1	0.464	No	No
Perceived Usefulness Post-Test 2	0.057	No	Yes
Perceived Ease of Use Post-Test 1	0.03	Yes	Yes
Perceived Ease of Use Post-Test 2	0.059	No	Yes
Adoption Readiness Post-Test 1	0.864	No	No
Adoption Readiness Post-Test 2	0.568	No	No

Large Firm Health Knowledge

Based on the results (Independent Sample $t = .550$, $df=45$, $p=.584$) the null hypothesis is not rejected at both the .05 and 0.1 levels. There is no significant evidence that the intervention had any affect on increasing gain scores of health knowledge from pre-test to the *first post-test* among intervention participants.

Table 41: Large Firm Health Knowledge Post-Test 1 Results

Gain Score Anova Pre-Test to Post-Test 1					
Construct: Health Knowledge					
Difference	0.2971	t Ratio	0.550495		
Std Err Dif	0.5397	DF	45		
Upper CL Dif	1.3841	Prob > t	0.5847		
Lower CL Dif	-0.7899	Prob > t	0.2924		
Confidence	0.95	Prob < t	0.7076		
Level	Number	Mean	Std Error	Lower 95%	Upper 95%
0	23	-0.13043	0.38566	-0.9072	0.64633
1	24	0.16667	0.37754	-0.5937	0.92708

Based on the results (Independent Sample $t=1.394$, $df=39$, $p=.1710$) the null hypothesis is not rejected at both the .05 and 0.1 levels. There is no significant evidence that the intervention had any affect on increasing gain scores of health knowledge from the pre-test to the *second post-test* among intervention participants.

Table 42: Large Firm Health Knowledge Post-Test 2 Results

Gain Score Anova Pre-Test to Post-Test 2 Construct: Health Knowledge					
Difference	1.0193	t Ratio	1.394581		
Std Err Dif	0.7309	DF	39		
Upper CL Dif	2.4977	Prob > t	0.171		
Lower CL Dif	-0.4591	Prob > t	0.0855		
Confidence	0.95	Prob < t	0.9145		
Level	Number	Mean	Std Error	Lower 95%	Upper 95%
0	23	-0.13043	0.4843	-1.11	0.8492
1	18	0.88889	0.54744	-0.218	1.9962

Large Firm Perceived Risk

Based on the results (Independent Sample $t= 1.613$, $df=45$, $p= .1137$) the null hypothesis is not rejected at both the .05 and 0.1 levels. There is no significant evidence that the intervention had any affect on increasing gain scores of perceived risk from pre-test to the *first post-test* among intervention participants.

Table 43: Large Firm Perceived Risk Post-Test 1 Results

Gain Score Anova Pre-Test to Post-Test 1 Construct: Perceived Risk					
Difference	1.2337	t Ratio	1.613181		
Std Err Dif	0.7648	DF	45		
Upper CL Dif	2.774	Prob > t	0.1137		
Lower CL Dif	-0.3066	Prob > t	0.0568		
Confidence	0.95	Prob < t	0.9432		
Level	Number	Mean	Std Error	Lower 95%	Upper 95%
0	23	-0.6087	0.54649	-1.709	0.492
1	24	0.625	0.53498	-0.453	1.7025

Based on the results (Independent Sample $t=1.935$, $df=39$, $p= .0603$) the null hypothesis is not rejected at the .05 and rejected at the 0.1 level. There is significant evidence at the 0.1 level that

the intervention had an affect on increasing gain scores of perceived risk from pre-test to the *second post-test* among intervention participants.

Table 44: Large Firm Perceived Risk Post-Test 2 Results

Gain Score Anova Pre-Test to Post-Test 2					
Construct: Perceived Risk					
Difference	1.8309	t Ratio	1.934973		
Std Err Dif	0.9462	DF	39		
Upper CL Dif	3.7448	Prob > t	0.0603		
Lower CL Dif	-0.083	Prob > t	0.0301		
Confidence	0.95	Prob < t	0.9699		
Level	Number	Mean	Std Error	Lower 95%	Upper 95%
0	23	-0.6087	0.62696	-1.877	0.6594
1	18	1.2222	0.70871	-0.211	2.6557

Large Firm Trust in Technology

Based on the results (Independent Sample $t = .573$, $df = 45$, $p = .569$) the null hypothesis is not rejected at both the .05 and 0.1 levels. There is no significant evidence that the intervention had any effect on increasing gain scores of trust in technology from pre-test to the *first post-test* among intervention participants.

Table 45: Large Firm Trust in Technology Post-Test 1 Results

Gain Score Anova Pre-Test to Post-Test 1					
Construct: Trust in Technology					
Difference	0.3315	t Ratio	0.573543		
Std Err Dif	0.578	DF	45		
Upper CL Dif	1.4957	Prob > t	0.5691		
Lower CL Dif	-0.8327	Prob > t	0.2846		
Confidence	0.95	Prob < t	0.7154		
Level	Number	Mean	Std Error	Lower 95%	Upper 95%
0	23	0.043478	0.41305	-0.7884	0.8754
1	24	0.375	0.40435	-0.4394	1.1894

Based on the results (Independent Sample $t = 1.28$, $df = 39$, $p = .209$) the null hypothesis is not rejected at both the .05 and 0.1 levels. There is no significant evidence that the intervention had any effect on increasing gain scores of trust in technology from the pre-test to the *second post-test* among intervention participants.

Table 46: Large Firm Trust in Technology Post-Test 2 Results

Gain Score Anova Pre-Test to Post-Test 2					
Construct: Trust in Technology					
Difference	1.0121	t Ratio	1.275602		
Std Err Dif	0.7934	DF	39		
Upper CL Dif	2.6169	Prob > t	0.2096		
Lower CL Dif	-0.5927	Prob > t	0.1048		
Confidence	0.95	Prob < t	0.8952		
Level	Number	Mean	Std Error	Lower 95%	Upper 95%
0	23	0.04348	0.52571	-1.02	1.1068
1	18	1.05556	0.59425	-0.146	2.2575

Large Firm Perceived Usefulness

Based on the results (Independent Sample $t = .738$, $df = 45$, $p = .464$) the null hypothesis is not rejected at both the .05 and 0.1 levels. There is no significant evidence that the intervention had any effect on increasing gain scores of perceived usefulness from pre-test to the *first post-test* among intervention participants.

Table 47: Large Firm Perceived Usefulness Post-Test 1 Results

Gain Score Anova Pre-Test to Post-Test 1					
Construct: Perceived Usefulness					
Difference	1.3243	t Ratio	0.737975		
Std Err Dif	1.7945	DF	45		
Upper CL Dif	4.9385	Prob > t	0.4644		
Lower CL Dif	-2.29	Prob > t	0.2322		
Confidence	0.95	Prob < t	0.7678		
Level	Number	Mean	Std Error	Lower 95%	Upper 95%
0	23	2.21739	1.2823	-0.365	4.8001
1	24	3.54167	1.2553	1.013	6.07

Based on the results (Independent Sample $t = 1.964$, $df = 39$, $p = .0567$) the null hypothesis is not rejected at the .05 and rejected at the 0.1 level. There is significant evidence at the 0.1 level that the intervention had an effect on increasing gain scores of perceived usefulness from pre-test to the *second post-test* among intervention participants.

Table 48: Large Firm Perceived Usefulness Post-Test 2 Results

Gain Score Anova Pre-Test to Post-Test 2			
Construct: Perceived Usefulness			
Difference	4.949	t Ratio	1.964157

Std Err Dif	2.52	DF	39		
Upper CL Dif	10.046	Prob > t	0.0567		
Lower CL Dif	-0.147	Prob > t	0.0283		
Confidence	0.95	Prob < t	0.9717		
Level	Number	Mean	Std Error	Lower 95%	Upper 95%
0	23	2.21739	1.6696	-1.16	5.594
1	18	7.16667	1.8873	3.349	10.984

Large Firm Perceived Ease of Use

Based on the results (Independent Sample $t = 2.238$, $df = 45$, $p = .030$) the null hypothesis is rejected at both the .05 and 0.1 levels. There is significant evidence that the intervention had an effect on increasing gain scores of PEOU from pre-test to the *first post-test* among intervention participants.

Table 49: Large Firm Perceived Ease of Use Post-Test 1 Results

Gain Score Anova Pre-Test to Post-Test 1					
Construct: Perceived Ease of Use					
Difference	3.16848	t Ratio	2.237744		
Std Err Dif	1.41593	DF	45		
Upper CL Dif	6.0203	Prob > t	0.0302		
Lower CL Dif	0.31666	Prob > t	0.0151		
Confidence	0.95	Prob < t	0.9849		
Level	Number	Mean	Std Error	Lower 95%	Upper 95%
0	23	-0.0435	1.0118	-2.081	1.9944
1	24	3.125	0.9905	1.13	5.12

Based on the results (Independent Sample $t = 1.946$, $df = 39$, $p = .0589$) the null hypothesis is not rejected at the .05 and rejected at the 0.1 level. There is significant evidence at the 0.1 level that the intervention had an effect on increasing gain scores of PEOU from pre-test to the *second post-test* among intervention participants.

Table 50: Large Firm Perceived Ease of Use Post-Test 2 Results

Gain Score Anova Pre-Test to Post-Test 2					
Construct: Perceived Ease of Use					
Difference	4.2657	t Ratio	1.946088		
Std Err Dif	2.1919	DF	39		
Upper CL Dif	8.6993	Prob > t	0.0589		
Lower CL Dif	-0.1679	Prob > t	0.0294		
Confidence	0.95	Prob < t	0.9706		
Level	Number	Mean	Std Error	Lower 95%	Upper 95%

0	23	-0.0435	1.4524	-2.981	2.8942
1	18	4.2222	1.6417	0.902	7.5429

Large Firm Adoption Readiness

Based on the results (Independent Sample $t = -.171$, $df=45$, $p = .864$) the null hypothesis is not rejected at both the .05 and 0.1 levels. There is no significant evidence that the intervention had any effect on increasing gain scores of adoption readiness from pre-test to the *first post-test* among intervention participants.

Table 51: Large Firm Adoption Readiness Post-Test 1 Results

Gain Score Anova Pre-Test to Post-Test 1 Construct: Adoption Readiness					
Difference	-0.0996	t Ratio	-0.17148		
Std Err Dif	0.5811	DF	45		
Upper CL Dif	1.0707	Prob > t	0.8646		
Lower CL Dif	-1.2699	Prob > t	0.5677		
Confidence	0.95	Prob < t	0.4323		
Level	Number	Mean	Std Error	Lower 95%	Upper 95%
0	23	0.391304	0.41521	-0.445	1.2276
1	24	0.291667	0.40647	-0.527	1.1103

Based on the results (Independent Sample $t = -.575$, $df=39$, $p = .568$) the null hypothesis is not rejected at both the .05 and 0.1 levels. There is no significant evidence that the intervention had any effect on increasing gain scores of adoption readiness from the pre-test to the *second post-test* among intervention participants.

Table 52: Large Firm Adoption Readiness Post-Test 2 Results

Gain Score Anova Pre-Test to Post-Test 2 Construct: Adoption Readiness					
Difference	-0.6135	t Ratio	-0.57484		
Std Err Dif	1.0673	DF	39		
Upper CL Dif	1.5453	Prob > t	0.5687		
Lower CL Dif	-2.7723	Prob > t	0.7157		
Confidence	0.95	Prob < t	0.2843		
Level	Number	Mean	Std Error	Lower 95%	Upper 95%
0	23	0.3913	0.70718	-1.039	1.8217
1	18	-0.22222	0.79938	-1.839	1.3947

Open Ended Response Results

Content analysis procedures were used to analyze the open-ended survey response items included on the small and large firm instrument. The items for these instruments were the same for both groups and the researcher developed codes that were both exhaustive and mutually exclusive for each quest set of questions. These codes were then assigned to each unit of response by independent coders who had been trained by the researcher on the category code definitions and coding process. Inter-rater reliability was calculated for each set of codes, using Krippendorff's alpha with significance set at $\alpha = 0.8$ (Krippendorff 2004). Items that did not have adequate rater agreement were not included in frequency counts.

Problems Associated with Drywall Dust

Inter-Rater reliability for the survey item "What are some potential problems associated with drywall dust and how could they affect your business?" was calculated and yielded a Krippendorff's alpha value of .933.

Table 53: Potential Problems with Drywall Dust Inter-Rater Calculations

Percent Agreement	Scott's Pi	Cohen's Kappa	Krippendorff's Alpha (nominal)	N Agreements	N Disagreements	N Cases	N Decisions
95.20%	0.933	0.933	0.933	158	8	166	332

The analysis of responses to this item of the survey instrument is summarized in Table 59 and Figure 9. Emergent themes were that there is a high recognition by employers that drywall dust could cause health, clean up, customer satisfaction, employee lost time and insurance problems for businesses in the drywall industry. The emergent themes associated with drywall dust creating a health problem for businesses were that there is a risk to worker health and that working around drywall dust causes problems with health as well as possible lost time from employee days away from work related to inhalation of drywall dust. Clean up concerns in regards to productivity and also customer satisfaction were also commonly reported as a problem drywall dust creates for businesses.

Table 54: Potential Problems with Drywall Dust Response Summary

Response Code/Category	Frequency	Percent	Sub-categories

Health	74	45%	Dust could be harmful to employees not wearing protection Health risks Employee safety Breathing problems Can cause health problems Negative effects on my employees health
Clean Up	39	23%	Dirty, more cleanup Dust accumulating on finished surfaces and/or equipment in occupied buildings clean up on remodels is time consuming
Lost Time at Work	22	13%	Health problems for workers causing missed time and delays in finishing projects on time More employee sick days Could cause trouble breathing so people could miss days
Customer Satisfaction	16	10%	Clients complain, possibly lose customers When dust settles it poses a problem when we do renovations which the client is still open for business People don't want dust throughout the house
Insurance	6	4%	Employee work comp or health insurance claims Increase in workers comp premiums
Legal	3	2%	Clean up insurance claims for damaged equipment and OSHA fines for not using proper dust masks Air conditioned filters, claims against company for AC problems
Quality	2	1%	Too much sanding affects finish Lingering dust affects paint jobs
Productivity	2	1%	Affects productivity Lost time due to drywall dust related ailments; productivity; and equipment costs
Government Regulation	2	1%	Govt regulation on employee exposure increase costs and reporting" Government regulation and record keeping
Total responses	166	100%	

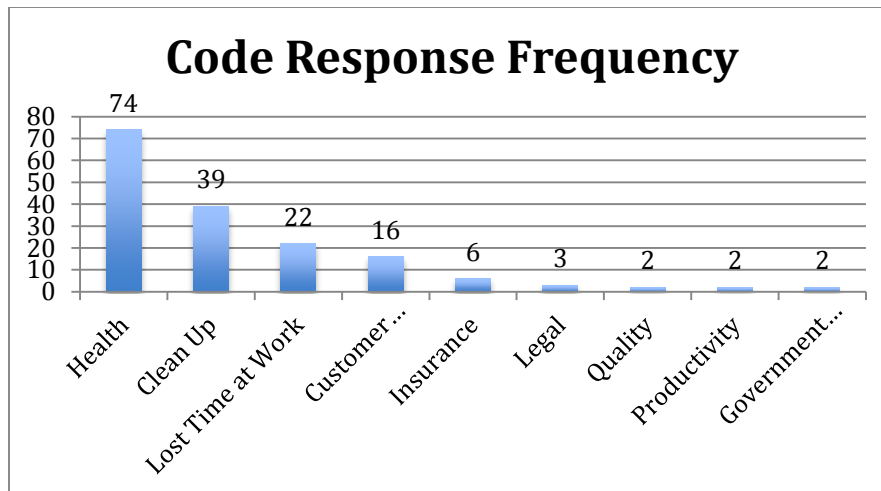


Figure 9. Problems with Drywall Dust Code Response Frequency

Opinions about Drywall Vacuum Sanders

Inter-Rater reliability for the survey item “What are your thoughts on using vacuum sanders as a dust control method in drywall sanding?” was calculated and yielded a Krippendorff’s alpha value of .92 as shown in Table 60.

Table 55: Inter-Rater Results for Vacuum Sanders

Percent Agreement	Scott's Pi	Cohen's Kappa	Krippendorff's Alpha (nominal)	N Agreements	N Disagreements	N Cases	N Decisions
94%	0.922	0.922	0.922	173	11	184	368

Units of response were coded first into type of reaction i.e. positive, negative, or neutral response and then coded by independent coders using determined categories set forth by the researcher. Emergent themes were that small and large firms view vacuum sanders as an effective method of controlling dust on a project although there are limitations to the tools’ effectiveness for regular usage. Many of the comments stated that the idea of vacuum sanding to control dust is good but that the limitations prevent wider adoption. Limitations of vacuum sander dust-control technology that have been found to exist in previous studies (Young-Corbett, 2009) relating to unfamiliarity with the technology, cost, quality, ease of use and productivity were also reported in the open ended responses. Contractors reporting regular usage of sanders were classified as champions of the product who have adopted the technology and have seen the benefits of use. Other findings included respondents who only used the technology if specified on projects and those who prefer alternate methods of dust control.

Response Code/Category	Unit Frequency	%	Sub-categories/Response Sample
Effectiveness	69	38%	Effective tool, controls dust, good idea,
Positive	60	87%	Work well, contains major portion of airborne dust Very good way to control dust Excellent way of controlling dust I like them because it keeps you healthy and saves time on clean up
Neutral	2	2.9%	Would seem to be effective and eliminate some of the additional clean up work I have no strong opinion regarding vacuum sanders
Negative	7	10.1%	They do not control all dust and take more time. I feel there are more effective ways. Vacuum sanders work well when working over finished floors, etc. but for everyday drywall I feel they would not work well. While I am familiar with vacuum sanders I don't know if they stop as much dust as they claim. Because of their size they cannot get into all areas of typical construction projects where detailed hand sanding is required.
Perceived Barriers/Limitations	45	24%	Perceived barriers to adoption/limitations of vacuum sanders
Positive	20	44.4%	Works fine if you change the filters as directed Sanders need to last longer Good method. Problem is they are so bulky and hard to break out for a little job I have used vacuum sanders in the past and still do and they work effectively when the machine is new. As the vacuums wear out they become less effective.
Neutral	7	15.6%	Sometimes it is not feasible to use in tight conditions. Could be useful once a finisher learned to use them proficiently Technology needs to improve on actual products
Negative	18	40%	I think they are somewhat hard to use and would take a learning curve and adjustment period to our production rates in taping. I have found them to be cumbersome and difficult to use Way to bulky, need to empty and/or clean the filter. They are a good idea but the application is not cost effective. Many commercial projects do not have power in the area that you are working. We cover large areas so moving a vacuum around cost time thus money. If the drywall mud is applied correctly there is not a lot of sanding that needs to take place between coats so moving a vacuum would be cumbersome. Final coat sanding would take longer using a vacuums just moving it around and dealing with the cord so most production employees will not even give it a try

Table 56: Vacuum Sander Response Analysis-Part 1

Table 57: Vacuum Sander Response Analysis Part 2

Response Code/Category	Unit Frequency	%	Sub-categories/Response Sample
Productivity	23	13%	Impact on Productivity or Time on the Project
Positive	8	34.8%	Very helpful and time saving Yo pienso que es una herramienta muy indispensable en estos dias ya que aumenta la productividad y la limpieza en el trabajo (I think it is a tool very essential in these days because it increases the productivity and cleanliness at work) A faster & more efficient way to sand
Neutral	2	8.7%	Time factor Time and Money
Negative	13	56.5%	Cumbersome, cuts down productivity It slows productivity but may be necessary due to project type They do not control all dust and take more time.
Champion	10	5%	Current User, Encourages Others to Use
Positive	10	100%	Vacuum sanders are a must when sanding drywall One of the best products in 10 years If you don't use one, start We use them in our company especially when dust is an issue with in the work space. It's a nice option to have. Have used it since the first survey, loved it.
Neutral			
Negative			
Quality	9	5%	Quality of Drywall Finish
Positive	0		
Neutral	0		
Negative	9	100%	Poor finish cumbersome clog easily slows productivity Expensive initial costs, can cause problems with finish. Probably due to inexperience we have had quality issues due to roughed up paper and swirl marks. I have found that vacuum sanders do not leave a quality as good as block sanding, also vacuum sanders require much more training for proper use

Table 58: Vacuum Sander Response Analysis Part 3

Response Code/Category	Unit Frequency	%	Sub-categories/Response Sample
Cost	9	5%	Cost
Positive	0		
Neutral	1	11.1%	Time and money
Negative	8	88.9%	Expensive equipment and filter costs Extra costs, extra maintenance, But they are a good tool for controlling dust when needed. Expensive initial costs, can cause problems with finish.
Specified Use Only	9	5%	Only if Project Specifies
Positive	0		
Neutral	6	66.7%	We'd likely use them if required We do not use vacuum sanders unless they are required on the job
Negative	3	33.3%	Slower production. Used only as required due to jobsite conditions (occupied spaces or Owner requirements). Only use them when we have to
New	8	4%	Unfamiliar with technology or would be open to try
Positive	1	12.5%	I like the idea but have yet to try one
Neutral	7	87.5%	I have never used one. If it really lessens employee risk and makes a better finish. Then I would be open to using them. Have never used these types of sanders.
Negative	0		
Alternate Method	2	1%	Alternate Method Preferred
Positive	1	50%	I think it is a good solution. The best solution would be to stop using dry wall finish and just use plaster instead.
Neutral			
Negative	1	50%	I think wet sanding is much more productive

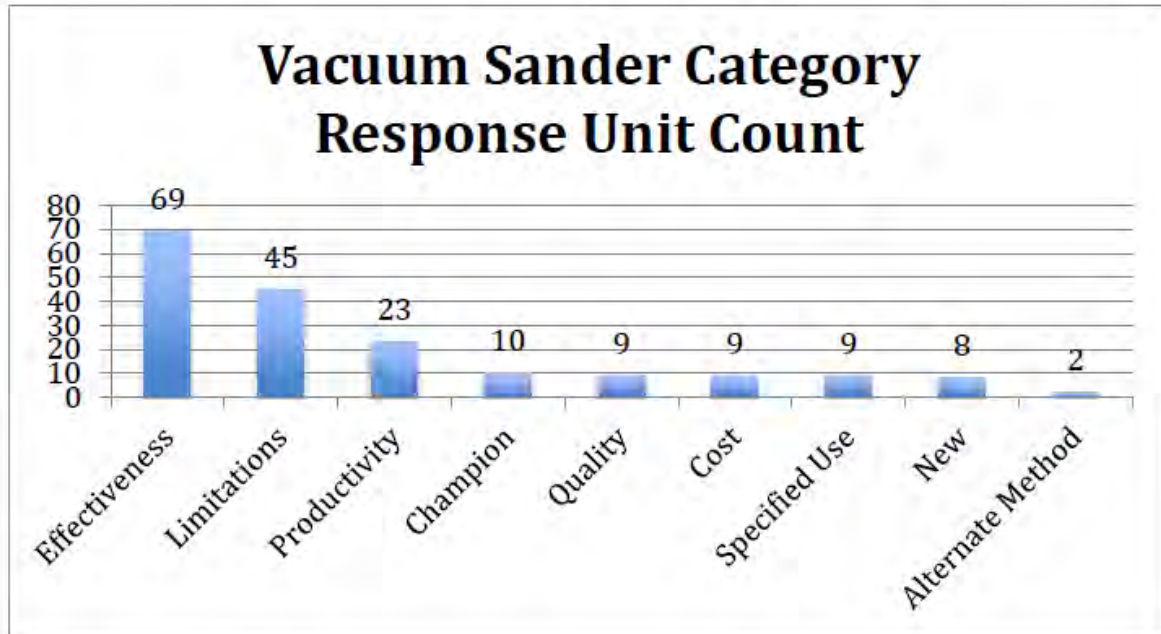


Figure 10. Vacuum Sander Unit Response Code Frequency

Of the 184 units of response to the survey item “What are your thoughts on using vacuum sanders as a dust control method in drywall sanding?”, 100 response units were coded as being positive in reaction to vacuums as a method of dust control with 59 units as negative reactions and 25 Neutral reactions.

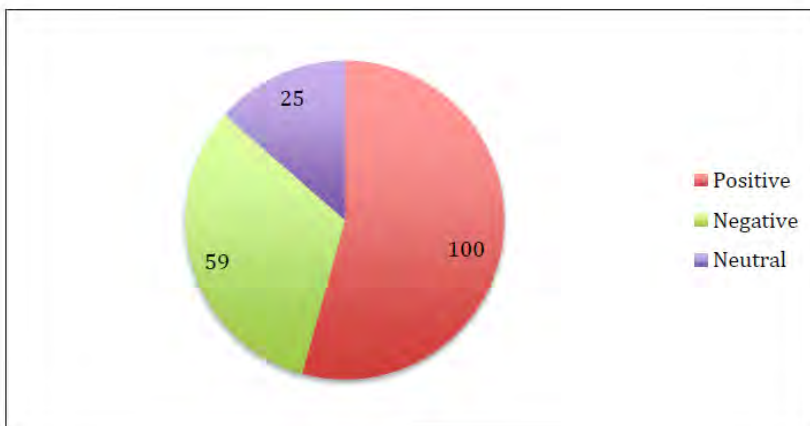


Figure 11. Frequency of Response Type, Vacuum Sanders as Dust-Control Method

Opinions about Low Dust Drywall Joint Compound

Inter-Rater reliability for the survey item “What are your thoughts on using low dust drywall joint compound as a dust control method in drywall sanding?” was calculated and yielded a Krippendorff’s alpha value of .886 as shown in Table 59.

Percent Agreement	Scott's Pi	Cohen's Kappa	Krippendorff's Alpha (nominal)	N Agreements	N Disagreements	N Cases	N Decisions
91.70%	0.886	0.886	0.886	143	13	156	312

Table 59: Inter-Rater Results for Low Dust Joint Compound

Units of response were coded first into type of reaction i.e. positive, negative, or neutral response and then coded by independent coders using predetermined categories set forth by the researcher. The breakdown of positive, negative and neutral response units is shown in Figure 12.

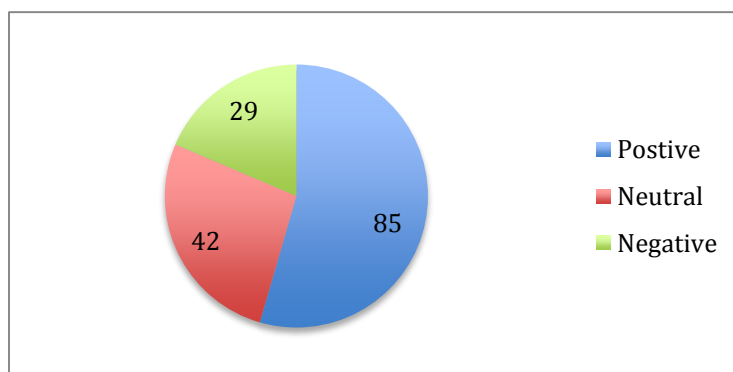


Figure 12. Frequency of Type of Response for Low Dust Joint Compound Used for Dust-Control

The analysis of response units to this item of the survey instrument is summarized in Tables 65-67 and Figure 15. Emergent themes were that small and large firms view low dust joint compound as a potential effective method of controlling dust on project although there are many who are unfamiliar with the product or have never tried it. Many of the comments stated that the idea of low dust joint compound to control dust is good but that the cost, limitations and unfamiliarity could be preventing wider adoption. Limitations of low dust joint compound technology that have been found to exist in previous studies (Young-Corbett, 2009) relating to unfamiliarity with the technology, cost, quality, ease of use and productivity were also reported in the open ended responses. Contractors reporting regular usage of low dust joint compound were classified as champions of the product who have adopted the technology and have seen the benefits of use. Other findings included respondents who only used the technology if specified on projects and those who prefer alternate methods of dust control.

Table 60: Low Dust Joint Compound Analysis Part 1

Response Code/Category	Unit Frequency	%	Sub-categories/Response Sample
Effectiveness	56	36 %	Effective as a Dust-Control Method for Health and Cleanup
Positive	40	71.4%	That would be helpful with dust control, cleanup and health problems Low dust joint compound is a much more effective and productive method. I have tried them. There seems to be less airborne dust. We have used it before, it is more expensive, but the job site clean up seems somewhat less

Neutral	6	10.7%	Needs to be a good product at equal priced It's often necessary Less dust to breath in
Negative	10	17.9%	It's a gimmick. If it's specified, we will buy it, otherwise no immediate interest in the product. Does not work well with my guys training wise/ not cost effective Doesn't work, misleading I've used it. Didn't see significant difference.
New	50	32%	Unfamiliar with the product or willing to try it
Positive	26	52%	If technology can make cost and product feasible, then great. Haven't used it before but would be willing to try it Good idea but have not had much exposure to it. I will try it.
Neutral	24	48%	I have not tried yet I don't have enough information about it. That would be fine if the compound were as workable as standard compounds
Negative	0		

Table 61: Low Dust Joint Compound Analysis Part 2

Response Code/Category	Unit Frequency	%	Sub-categories/Response Sample
Quality	23	15%	Quality of Finish
Positive	7	30.4%	Has started using it and it does cut down on some dust. It finishes pretty similar Works better than conventional Works well, we should use this more often As long as finished results are the same

Neutral	5	21.7%	Low dust only means that becoming airborne, it falls straight down. Still the same amount of dust. We use this as well my only concern is with the quality of the product whether it will hold up over the years Needs to be a good product at equal priced
Negative	11	47.8%	Doesn't finish as well. Have not seen remarkable difference when used. Have also been told it is not as hard and scratches easier when dry. Usually these type of products do not produce the quality of wall finish that is required and harder to use. Does not work as well as conventional tape and mud.
Cost	13	8%	Cost of Product/Productivity
Positive	5	38.5%	If it works that would be a great alternative depending on cost We have used it before but it is more expensive but the jobsite cleanup seems somewhat less I think it would speed up production and cut labor cost
Neutral	2	15.4%	Needs to be a good product at equal priced Make it economically based on the industry tough economy.
Negative	6	46.2%	Does not work well with my guys training wise/ not cost effective Overall finish is more costly As I can tell it is not cost effective

Table 62: Low Dust Joint Compound Analysis Part 3

Response Code/Category	Unit Frequency	%	Sub-categories/Response Sample
Champion	6	4%	Current User, Encourages Usage
Positive	6	100%	We started using this product This is our preferred method Very fond of this method
Neutral	0		

Negative	0		
Alternate Product	5	3%	Suggest Alternate Method
Positive	1	20%	Helps but not the solution
Neutral	3	60%	I don't think there is a low dust dry wall compound. Oh wait, there is. It's called plaster. Our company does not use premixed mud
Negative	1	20%	Our tapers are very particular regarding the manufacturer of our joint compound. We have used one brand for years. Low dust compound affects our productions rates negatively.
Specified Use	3	2%	Only Use When Specified
Positive			
Neutral	2	66.7%	We only use when specified Price is a factor, started to see more jobs specify this for use
Negative	1	33.3%	It's a gimic. If it's specified, we will buy it, otherwise no immediate interest in the product.

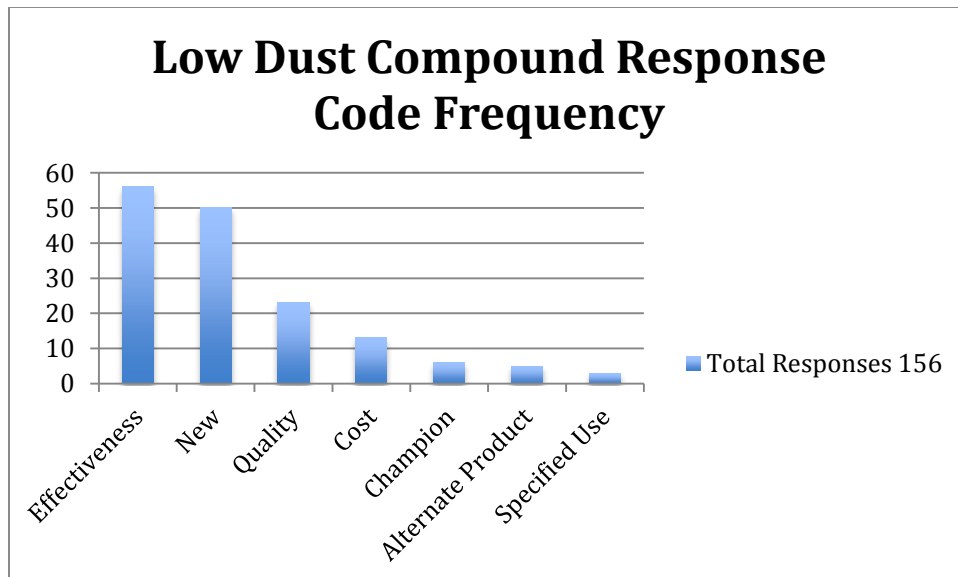


Figure 13. Low Dust Joint Compound Response Code Frequency Results

Summary

Significant gains in construct scores were found at both the .05 and 0.1 significance levels in all three interventions. Significant gains in the employee intervention included self-efficacy, trust in technology and adoption readiness. Significant gains in the small firm intervention included perceived risk, trust in technology, perceived ease of use, and adoption readiness. Significant gains in the large firm intervention included perceived risk, perceived usefulness, and perceived ease of use.

Open-ended response items were analyzed using content analysis procedures utilizing inter-rater reliability procedures to determine and report findings. Emergent themes from the open-ended questions included a high reporting of health risk and clean up as a potential problems drywall dust could pose to businesses and both the effectiveness and limitations of vacuum sanders and low dust joint compound as dust-control methods. The findings of both the gain score analysis of the theoretical constructs and open-ended response analysis will serve as the basis for discussion of the effectiveness of the interventions in Chapter 5.

Discussion

The large firm intervention construct gain scores that were shown to have a significant increase among intervention group participants were perceived risk, perceived usefulness, and perceived ease of use. The construct gain scores that were not found to be significant in the large firm intervention were health knowledge, trust in technology, and adoption readiness.

Large Firm Perceived Risk Discussion

Perceived risk to health gain scores for the large firm intervention group were found significant on the second post-test which occurred three months after the initial pre-test, intervention, and initial post-test. The first post-test gain scores for perceived risk were not found to be significant. This result of the first post-test not showing a significant increase in gain scores was unexpected based on previous interventions using the perceived risk construct of the HBM. The significance in gain scores increase for the second post-test supports previous intervention examples discovered through the literature review which also used the HBM to increase participant's perceived risk include interventions to reduce smoking, interventions to increase breast cancer screening, increased nutrition at worksites, increase in colorectal cancer screenings, increased diabetes awareness and prevention, increased vaccination participation and various other health related concerns (Bastani 1995; Conrad et al. 1996; Vernon 1997; Aoun et al. 2002; Abood 2003; Dempsey 2006). The online training session outlined potential risks to health from overexposure to drywall dust. The mean scores of participants, initial (4.52) and the first post-

test (4.58) reveal that there is a lower level of perceived risk and that the intervention failed to immediately increase the perceived risk to health threat large firm owners view working around drywall to be. Over time based on the significant increase in gain scores, perceived risk to health increased among large firm owners that supported the use of the perceived risk construct. The main elements that make up the perceived risk construct are: perceived susceptibility and perceived severity (Rosenstock 1960; Rosenstock 1988; Elder 1999). These elements are the major determining factors that cause people to adopt or continue practices that are meant to protect a person's safety and health. The first is the degree to which a person feels he or she is susceptible to a certain health problem or disease. The second is the severity the person believes that contracting the disease or health problem would have serious consequences to them (Rosenstock 1960).

Explanations for the lack of gain score increase in the initial post-test could be that the online intervention did not adequately communicate the severity of working around drywall dust or that employers do not feel that their workers are susceptible problems relating to dust inhalation. Considering that the health rewards that adopting individuals will gain may be delayed in time and are not immediately visible and may not be viewed as being severe enough to take immediate action, large firms may not view have viewed exposure as an immediate risk. The consequence of not adopting the innovation on their employee's health may never occur. Preventative innovations such as the one conducted in this research have been perceived as having low relative advantage as compared to other innovations that are designed to create a profit (Rogers 2002). This model focuses on perceptions, beliefs and other personal characteristics that influence whether a person feels at risk for a certain health problem and whether they position themselves to change certain health behaviors, health practices and/or to utilize health care services (Lux 1994). Open-ended responses of contractors showed that while there was not a high level of perceived risk, health related days away from work, potential health problems, and insurance premium increases due to worker's compensation claims were a risk for their companies and that there was a need to control employee exposure.

Large Firm Perceived Usefulness Discussion

Perceived usefulness (PU) gain scores for the large firm intervention group were not found significant on the immediate post-test following the intervention but were found to be significant on the second post-test which occurred three months after the initial pre-test, intervention, and initial post-test. The outcome of increased PU of large firms over time was expected at the outset of this research and is consistent with past interventions using the construct of PU combined with the PEOU construct of the TAM to increase PU. The initial failure to increase PU scores was not expected based on previous interventions using the TAM. By showing the large firm owners how the tool worked and the advantages that using the tool provided to their firm through online video, the intervention demonstrated perceived usefulness to the firm owners. This is consistent with interventions using this construct of the TAM including introducing new computer management systems in manufacturing firms, increasing physician's decisions to adopt telemedicine and introducing a new interactive online help desk system (Hu 1999; Venkatesh 2000b, 2000c). Due to the lack of hands-on demonstrations of the tool online and not in person along with hand-on training, and giving the technology and not giving the tool to the large firms

to use, the initial PU of large contractors could have been affected when compared with the in-person intervention small firm recipients received.

Large Firm Perceived Ease of Use Discussion

Perceived ease of use (PEOU) gain scores for the large firm intervention group were found significant on both the initial post-test and the second post-test which occurred three months after the initial pre-test, intervention, and initial post-test. The post-test gain scores did show significant improvement that supports the TAM methods for using PEOU to enhance personal acceptance of technology. This is consistent with interventions combining this construct of the TAM with the construct of PU. Interventions including introducing new computer management systems in manufacturing firms, increasing physician's decisions to adopt telemedicine and introducing a new interactive online help desk system have successfully used these constructs to also improve PEOU (Hu 1999; Venkatesh 2000b, 2000c). As companies were shown video of the tool in use, they were able to become familiar with the technology and as experience is gained, PEOU is increased. The influence of PEOU is greater in organizational settings where adoption is mandatory while in voluntary settings PU is the stronger determinant of behavior intention to use technology (Brown 2002). In drywall companies where the use of vacuum sanders will be mandated, the PEOU of the technology is important to increase adoption readiness among employees. In companies where the use of vacuum sanders is not mandated, then PU will most likely be the stronger determinant on behavioral intentions to use the sanders.

Large Firm Health Knowledge Discussion

Health knowledge gain scores for the large firm intervention group were not found to be significant on the first post-test which immediately followed the intervention or on the second post-test three months following the intervention. While the lack of gain score increase was unexpected at the onset of the research upon review of the initial mean scores of health knowledge among participants, the level of health knowledge about working around drywall dust and the effects it can have on health was evident among large firms. Another factor that could be present is that firm owners could be hesitant in reporting health knowledge that could expose them to liability. Many responses both on the pretest and post-tests of large firm participants were scored as "neither disagree or agree" which could provide contractors an option for not answering truthfully their level of health knowledge to remove any liability they perceived to have. Initial mean scores for health knowledge were (5.00) based on a 7-point scale. Post-test mean scores for the immediate post-test (5.05) and for the three month follow up post-test (5.61) were slightly higher than the initial pre-test scores but overall gain scores were not found to be significant. The mean scores for health knowledge items shows there was some increase in health knowledge among some large firms, but with the mean scores being scored on a scale of 1-7, there was already a level of health knowledge among small firms in the drywall industry about the possible health effects drywall dust can pose. This was also evident in the open-ended responses from many of the contractors stating that health risks or health problems are a potential

problem when working around drywall dust. Results from other worksite health promotion activities have yielded promising yet modest health behavioral changes while evidence suggests that those who participate in workplace health promotion interventions achieve positive health outcomes (Linnan 2001). Helping large firms to become aware of the risks they are exposed to by increasing health knowledge, perceived susceptibility, perceived severity and helping them to break down any perceived barriers by teaching health knowledge and allowing them to realize the benefits of healthy behaviors can easily be adapted to work site situations and hazards (Conrad et al. 1996).

Large Firm Trust in Technology Discussion

Trust in technology gain scores for the large firm intervention group were not found to be significant on the first post-test which immediately followed the intervention or on the second post-test three months following the intervention. The lack of significance in gain score differences for trust in technology on the large firm intervention was unexpected. Possible explanations for this lack of gain could be related to the findings in the open ended responses from employers stating that while the vacuum sanding technology is a good idea and reduces dust, the quality of finishes could be diminished. Unlike the worker and small firm intervention, the large firm owners did not receive hands-on demonstrations of the vacuum sanders and that might explain the lack of gain score increase. A previous intervention dealing with implementing new working methods to reduce the knee strain in floor layers found that workers can be reluctant to accept changes in working methods because they will at least for a period decrease their work intensity and output found that workers who did not implement the new practices immediately after the interventions did not tend to use them later and have not increased their trust in the new system (Jensen and Kofoed 2002). If the large firm participants in the intervention were not able to use the sanders immediately after the intervention in their work or did not have access to the technology, it could explain the lack of increased gain scores for trust in technology.

The online intervention failed to enhance trust in technology by the strengthening the individual's expectation that the technology exhibits the elements of predictability, reliability and utility (Lippert 2005). The intervention showed the effectiveness of the technology and allowed the users to interact with the technology and see potential benefits of using the tool similar to previous studies where trust in technology was built in physicians accepting new technology when the perceived benefits could be seen and the tangible results of the technology are made apparent to users (Yi et al. 2006). The benefits shown through an online intervention may not have provided enough support to the participants to promote trust in the technology.

Large Firm Adoption Readiness Discussion

Adoption readiness gain scores for the large firm intervention group were not found to be significant on the initial post-test or on the second post-test which occurred three months after the initial pre-test, intervention, and initial post-test. These results were unexpected because as in other interventions that have been successful at increasing adoption readiness, the elements of relative advantage, compatibility, complexity, and observability of the DOI model were incorporated into the design of the intervention (Rogers 2003). The lack of the DOI element of triability included in the large firm intervention could explain the lack of adoption readiness gains that were found in the small firm interventions, which did allow for trialability. Large firms might not have shown impact due to the technology being new to them and they did not have the same opportunity to use tool to determine if the technology did meet all the elements of the DOI model.

The lack of increase in adoption readiness does not support other interventions successfully using these elements of the DOI to increase adoption readiness such as an intervention to increase the intention of utility companies to adopt energy conservation (Vollink 2002). Other possible explanations for this lack of gain could be related to the open-ended findings relating to the concern over the quality of finish the vacuum sanders produce. An innovation must allow the adopter to execute actions that increase the organization's performance (Toole 1998). If large firms did not perceive the technology to increase their performance, their adoption readiness level could potentially be affected. Open-end responses from large firms also noted that barriers found previously in studies (Young-Corbett 2009) are still prevalent in large firms. Quality of finish and production times as well as difficulty in moving vacuums around on jobsites while on scaffolding were listed by large firms as barriers to further adoption of vacuum sanders as viable dust control technology for large firms.

Open Ended Response Discussion

The open-ended responses obtained from the small and large firm intervention participants provided insight into the thoughts of contractors regarding the problems drywall dust poses to aspects of their business, how they view vacuum sanders as an option to control dust and how they view using low-dust joint compound as a dust-control method. Responses were analyzed using content analysis procedures. The majority of contractors surveyed reported that drywall dust is a concern for their businesses. Problems that were reported related to matters of health risks, clean up, customer satisfaction or lost time at work or legal issues. Some comments related that employee lost time due to inhalation of dust or dust related illness has had an impact on their business. Several contractors responded that they were aware of the potential problems dust poses but felt increased dust regulations were unnecessary and that as long as masks are used properly the workers were not susceptible to dust related health problems.

Contractors viewed vacuum sanders as a good option for dust-control however many also listed limitations regarding the use of vacuum sanders in regards to the quality, cost of equipment and maintenance, ease of use, and production time it took to use the tools. This was consistent with the findings of previous studies (Young-Corbett and Nussbaum 2009a) conducted regarding the implementation of dust-control technology. Large firms also listed logistical reasons that the use of vacuum sanders could be difficult to implement on larger projects. Some of these reasons included a lack of power to vacuums, and larger areas having to be sanded using scaffolding would prevent the effective use of vacuum sanders. Firms are seeing more projects specifying the use of vacuum sanders on projects particularly in hospital and information technology equipment work areas. One company noted that since the initial intervention they had used the tool and loved it. The introduction of vacuum sanders to companies who had not used the technology was also an aim of the interventions.

Contractors views of low-dust joint compound showed that many are still unaware of the product or do not have much experience with the product and some mentioned they would be willing to try it. The emergent theme from the content analysis was that the participants thought the idea of low-dust compound was good and the control option they would choose if the cost and quality of traditional joint compound could be achieved. Several contractors reported that they have seen more projects specifying low-dust compound and that the quality of the product is improving. Some users of low-dust compound listed cost and quality limitations with the product noting that the finished product is softer, and does not accept paint the same as traditional joint compound. Other participants felt that the product was a gimmick and did not reduce the amount of dust.

Conclusion

Recommendations for the further development of construction safety and health research have been formulated based on the results of this research. This research has yielded significant findings in the use of theory-based interventions to increase the intent to use dust-control technology among workers, small firms and large firms in the drywall industry. The problem of health and safety intervention research to increase intention to use control methods in construction is broad and complex. Addressing health and safety in the construction industry is more difficult than in a fixed industrial setting. The workplace and workforce are always changing so it makes any health or safety intervention difficult to implement or evaluate (Kramer et al. 2009). The regular change in workforce demographics is a critical factor in the allocation of safety educational and training resources. Better educated /trained workers are more aware of the hazards in the work environment and are more likely to take action to protect themselves (Brunette 2005).

The information obtained in this research has provided insights into the implementation of successful theoretical based drywall dust-control usage intervention practices using the HBM, TAM and DOI models. Measurement of the impacts of safety and health training poses a difficult challenge for the training community to quantify. Intervention evaluations should provide a theoretical basis for the intervention, create an intervention powerful enough to be measured, implement valid measurement instruments, and use appropriate statistical analysis (Becker 04). As Lipsey notes (1993) theory based research has the potential to support inferences about new and successful interventions. Theory based research can provide conceptual frameworks for improving hazard control methods as well as helping researchers design studies that provide more interpretable and generalizable results (Goldenhar 1996).

It is recommended that the construction industry needs to continue to develop effective intervention strategies using the methods used in this research and improving on theoretical based methods to increase the safety of those in the industry. The success of interventions relies heavily on the relative advantage the innovation provides to the users. Successful interventions to increase innovation usage requires that rewards be shared between the players involved in the construction process including clients (Manseau and Shields 2005). The PtD adoption readiness model integrating the HBM, TAM and DOI models has produced some significant results for increasing the intent to use control methods and should continue to be used and refined to design, implement and evaluate future safety and health interventions.

Worker Intervention Recommendations

Worker intervention training should be worker centered, include hands on training, and seek to motivate employees to remain active in improving their working conditions. The significant gain score increases that were found for the constructs of self-efficacy, trust in technology, and adoption readiness support the continued use of these theoretical constructs in future interventions. While significant gains were not found in the constructs of health knowledge, or perceived risk, it is recommended that these elements continue to be implemented into future

health and safety intervention research due to workers needing to be informed of hazards they are exposed to. Greater focus should be placed on the severity and susceptibility of exposed hazards and attention given to the ability of the individual to control the hazard. The construct of organizational trust was also not found to yield significant increase in gain scores among workers. Worker hesitation to report distrust in organization could be reflected in these results. The use of this construct is still recommended based on a study aimed at influencing the attitudes and behaviors in safety in the UK construction industry, (Langford 2000) where it was determined that when employees believe that the company and management care about their personal safety, they are more willing to co-operate to improve safety performance in the organization.

An important limitation was the reliance on health and safety professionals as the primary means of presenting information in the intervention. Future studies should focus on ways to utilize peers or suppliers in delivering health and safety messages and encouraging owners to make changes. While the use of certified trained instructors is recommended for use in training sessions to support credibility, it is recommended that the use of peer training be used in future worker interventions for occupational safety and health training which has been reported to be more successful for increasing self-efficacy among trained workers than the use of professional trainers in a study (Becker 2004) comparing worker activities before and after safety trainings. While worker training is an important element of improved safety on jobsites, it can be severely enhanced or hindered by the organization to which it is applied (Becker 2004).

Small Firm Intervention Recommendations

The small firm intervention was found to be the most effective of the three interventions based on the theoretical construct gain score results. The significant gain score increases that were found for the constructs of perceived risk, trust in technology, perceived usefulness, perceived ease of use and adoption readiness support the continued use of these theoretical constructs in future interventions. While significant gains were not found in the construct of health knowledge, it is recommended that these elements continue to be implemented into future health and safety intervention research due to employers needing to be informed of hazards their employees are exposed to. Greater focus should be placed on the severity and susceptibility of exposed hazards and attention given to the ability of the individual to control the hazard. Introducing innovations in construction interventions should not only focus on how the technology can be of benefit in daily work, but also should emphasize the delivery of long-term benefits of use (Chau 1996). Future interventions dealing with small firms should focus on presenting the proposed change in work practice as reasonable to those who are asked to utilize it and that it is consistent with current methods. This is also supported in an intervention study (Hess et al. 2004) to reduce risk factors for lower-back disorders in concrete laborers where the first step was to get support from the company to invest financially and philosophically in trying a new intervention.

Large Firm Intervention Recommendations

The large firm intervention was found to be the least effective of the three interventions based on the theoretical construct gain score results. The significant gain score increases that were found for the constructs of perceived risk, perceived usefulness, perceived ease of use support the continued use of these theoretical constructs in future interventions. While significant gains were not found in the construct of health knowledge, it is recommended that these elements continue to be implemented into future health and safety intervention research due to employers needing to be informed of hazards their employees are exposed to. Greater focus should be placed on the severity and susceptibility of exposed hazards and attention given to the ability of the individual to control the hazard. The lack of gain score increases for the constructs of trust in technology and adoption readiness could be explained by the intervention being delivered as a web-based intervention instead of in person. Other factors that could have impacted gain scores could have been the lack of the DOI elements of triability and in person observability that were lacking in the online large firm intervention. Triability is an important element of intervention effectiveness that is recommended to be implemented in future interventions.

It is recommended that the use of online interventions to increase usage of innovations in the construction industry should be accompanied with some form of triability which is important to increase the trust in technology and adoption readiness of participants. Purchasing departments play a large role in the adoption of new products and methods in large companies and are responsible for the decisions made and innovative risks taken (Koebel 2008). Purchasing agents must be convinced of a product's benefits and that manufacturers will support their products. Understanding products and processes and the potential benefits that could be realized through the use of new innovations could help purchasing agents make informed decisions about adopting safety and health innovations. As experience is gained in using the innovation and reliability and accurate results are proven then trust will increase which will in turn increase adoption readiness (Parasuraman and Riley 1997).

Recommendations for Future Research

The intent of this research was to use theoretical based constructs to design, implement and evaluate interventions for workers, small firms and large firms in the drywall industry aimed at increasing intention to use engineered dust-control methods. Additional research evaluating the effectiveness of the PtD Adoption Readiness Model (PtD ARM), which integrated the HBM, TAM and DOI models, for enhancing intent to use new technologies and actual usage of new technologies in the construction industry should be explored. The PtD Adoption Readiness Model should be expanded beyond the drywall finishing trade and should be implemented into other sectors of the construction industry. Using the lessons learned from the implementation of dust-control usage among drywall workers, small firms and large firms, other health and safety interventions could build upon the findings and develop similar interventions to increase intentions to use health and safety controls for other areas of construction. Laws and regulations will be important as part of the infrastructure of safety management, but beliefs, and actions will have a stronger influence upon the safety climate of construction sites (Langford 2000). By using a more interdisciplinary approach, a stronger foundation will be developed for conducting intervention research in occupational health and safety.

Measurement of impacts of safety and health training remains the most difficult outcome for the training community to measure. Intervention research is the study of planned and applied activities designed to produce designated outcomes by applying scientific methods to measure the impact of health interventions. Such evaluation should carefully incorporate a theoretical basis for the intervention, an intervention powerful enough to be measured, a rigorous study design, valid measurement instruments, and appropriate use of statistical analysis (Becker 2004).

Drywall sanding innovations are modular in that they change the way the work is performed but leave the other components of the systems in place. Additional research is recommended to improve wall finish systems that would provide the function and look of drywall but where sanding is eliminated to where worker exposure to airborne dust is not a problem. If changes to wall systems are not feasible continued research emphasis should be placed on the product development of low-dust joint compound in terms of quality and cost to promote the wide spread development of its use through the drywall industry. Building the control method into the product itself takes away the decision factor of employees on whether to use dust-control tools and will reduce equipment costs for employers.

Based on the lack of significance of gain scores on the large firm intervention, it is recommended that additional research be conducted on the effectiveness of online training interventions in the construction industry. Web-based interventions have potential advantages for reaching large numbers of candidates, can provide individually tailored messages based on participant knowledge, and can appeal to large numbers of users without the cost of traditional on-site interventions. Internet interventions don't always transfer directly what has worked in face-to-face interventions and considerations for the development and testing of interventions online should be carefully considered. Successful interventions using the HBM elements and the Internet to promote healthy behaviors including an intervention demonstrating the effectiveness of tailored diabetes health information on participant's health practices (Gottlieb, 2000) and behavioral interventions related to chronic back pain (Lorig et al., 2002) show the promise of using web-based interventions to increase healthy behaviors (Salyers Bull 2004). Despite the growing number of Web-based health improvement programs in the workplace, in comparison to traditional in person interventions, there has been relatively little evaluation of Web-based workplace interventions, particularly preventive interventions targeting multiple health behaviors (Cook 2007).

Additional research should be conducted with large firm drywall contractors to determine efficient and cost effective ways of implementing the vacuum sanders as dust-control technologies into their operations. Increased efficiency and productivity in using this control method could increase the perceived relative advantage of using the technology that in turn could increase intent to use vacuum sanders in large firms.

Summary

The overall goal of this study has been to change the behavior of drywall dust finishers by implementing dust control technologies. The findings of the strategic dust-control usage interventions for workers, small firms and large firms in the drywall industry have been discussed in this chapter. Evaluation of theoretical construct measurement performance was discussed for each of the three interventions as well as a discussion on the open-ended response evaluations. Recommendations for construction industry health and safety intervention research practice were outlined along with recommendations for future research and implications of the research. All three interventions showed elements of effectiveness in increasing various constructs of the theoretical models used and future interventions can use this work to help build a body of knowledge to strengthen intervention research in the construction industry

Publications Resulting from Project

Journal Articles

Popov, G, Blunt, LA, McGlothlin, G, Young-Corbett, D, Zey, JN, Heckel, P, [submitted September 2011, accepted January 2012]. Integrating Prevention through Design in Undergraduate Curricula. *Professional Safety: Journal of the American Society of Safety Engineers*. (Specific Aim 1)

Young-Corbett, D.E. [submitted May 2011, accepted with revisions, November 2011, revised March 2012]. Prevention through Design (PtD) Approaches to Control Construction Health Hazards. *Journal of Construction Engineering and Management*. American Society of Civil Engineers. (Specific Aim 1)

Weidman, J.E., Young-Corbett, D.E., Koebel, C.T., Montague, E.N. [submitted May 2011, accepted with revision December 2011, revised May 2012]. Prevention through Design Adoption Readiness Model (PtD ARM): An Integrated Conceptual Model. *Health Education and Behavior*. (Specific Aim 1)

Young-Corbett, D.E., Weidman, J.E., Koebel, C.T., [submitted May 2012, accepted with revisions August 2012]. A Validated Survey Instrument for Assessing Prevention through Design Adoption Readiness. *Health Education and Behavior*. (Specific Aim 2)

Weidman, J.E., Young-Corbett, D.E., Koebel, C.T., An effective intervention to improve construction worker use of engineering controls. *Journal of Safety Research, in press*. (Specific Aim 3)

Weidman, J.E., Young-Corbett, D.E., Koebel, C.T., An effective intervention to improve small construction firm adoption of engineering controls. *Journal of Safety Research, in press*. (Specific Aim 4)

Weidman, J.E., Young-Corbett, D.E., Koebel, C.T., An effective intervention to improve large construction firm adoption of engineering controls. *Journal of Safety Research, in press*. (Specific Aim 5)

Book Chapter

Young-Corbett, DE: [submitted January 2012, accepted July 2012] Prevention through Design: Eliminating Occupational and Environmental Risk through Design of Equipment, Work, and Systems. *Chapter in: The Handbook of Industrial and Systems Engineering*, 2nd Edition. Taylor and Francis, CRC Press. Boca Raton, FL. Badiru, AB, editor.

Conference Proceedings

Bhattacharjee, S.*, Ghosh, S.*, and Young-Corbett, D. [2010]. The Next Step to Improve Safety – Prevention through Design. Proceedings of 2010 Associated Schools of Construction Region III Conference. October 20-23, 2010. Downers, GA, USA.

Bhattacharjee, S., Ghosh, S.*, and Young-Corbett, D. [2011] The Next Step to Improve Safety: Prevention through Design. *47th Annual International Conference of Associated Schools of Construction*. April 6-9, 2011. Omaha, Nebraska, USA.

Ghosh, S.*, and Young-Corbett, D. [2011]. Barriers to the Adoption of Prevention through Design (PtD) Controls among Masonry Workers. *International Council for Research and Innovation in Building and Construction Conference (CIB W099 Conference 2011)*, Washington, DC, USA.

Weidman, J.E*, Young-Corbett, D., Koebel, C.T., Fiori, C., and Montague, E.N. [2011]. Prevention through Design: Use of the Diffusion of Innovation Model to Predict Adoption. *International Council for Research and Innovation in Building and Construction Conference (CIB W099 Conference 2011)*, Washington, DC, USA.

Ghosh, S.*, and Young-Corbett, D. [2011]. Barriers to the Adoption of Prevention through Design (PtD) Controls among Masonry Workers. *International Council for Research and Innovation in Building and Construction Conference (CIB W099 Conference 2011)*, Washington, DC, USA, August, 2011.

Weidman, J.E.*, Young-Corbett, D., Koebel, C.T., Fiori, C., and Montague, E.N. [2011]. Prevention through Design: Use of the Diffusion of Innovation Model to Predict Adoption. *International Council for Research and Innovation in Building and*

Construction Conference (CIB W099 Conference 2011), Washington, DC, USA. August, 2011.

Dissertation/Theses

Weidman JE [2012] Dust-control Usage: Strategic Technology Intervention, Ph.D. Dissertation, Virginia Tech. (Specific Aims 1 – 5)

Otero, Yuanivel [2011] Time and Motion Analysis of Drywall Sanding Operations, MS Thesis, Virginia Tech. (Specific Aim 5)

Sharma, Siddarth [2009] Human Factors Design of Construction Sanding Tools, MS Thesis, Virginia Tech. (Specific Aims 3 and 4)

Inclusion of Gender and Minority Participants

Study Title: Dust-control Usage: Strategic Technology Intervention
Total Enrollment: 172 **Protocol Number:** FWA00000572
Grant Number: 5 U60 OH009761-03 Project ID 658

PART A. TOTAL ENROLLMENT REPORT: Number of Subjects Enrolled to Date (Cumulative) by Ethnicity and Race				
Ethnic Category	Females	Males	Sex/Gender Unknown or Not Reported	Total
Hispanic or Latino	0	84	0	84 **
Not Hispanic or Latino	0	88	0	88
Unknown (individuals not reporting ethnicity)	0	0	0	0
Ethnic Category: Total of All Subjects*	0	172	0	172 *
Racial Categories				
American Indian/Alaska Native	0	0	0	0
Asian	0	0	0	0
Native Hawaiian or Other Pacific Islander	0	0	0	0
Black or African American	0	0	0	0
White	0	172	0	172
More Than One Race	0	0	0	0
Unknown or Not Reported	0	0	0	0
Racial Categories: Total of All Subjects*	0	172	0	172 *
PART B. HISPANIC ENROLLMENT REPORT: Number of Hispanics or Latinos Enrolled to Date (Cumulative)				
Racial Categories	Females	Males	Sex/Gender Unknown or Not	Total
American Indian or Alaska Native	0	0	0	0
Asian	0	0	0	0
Native Hawaiian or Other Pacific Islander	0	0	0	0
Black or African American	0	0	0	0
White	0	84	0	84
More Than One Race	0	0	0	0
Unknown or Not Reported	0	0	0	0
Racial Categories: Total of Hispanics or	0	84	0	84 **

Inclusion of Children

Not applicable

Materials Available for Other Investigators

All study methods and results have been disseminated to the scholarly community via the publications described herein.

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Appendix: Validated Survey Instruments

Project ID 10183 - Prevenir Cadas: An LHA-Based Approach to Safety Education among Latino Roofers

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Abbreviations

ARSMA-II	Acculturation Rating Scale for Mexican-Americans-II
CATS	Computer-Assisted Telephone Surveys
CPWR	Center for Construction Research and Training
DASH	Disabilities of the Arm, Shoulder, and Hand
HOLA counties in NC	Non-profit organization serving Latino communities of Wilkes and surrounding counties in NC
JCQ	Job Content Questionnaire
LHA	Lay Health Advisor
PPE	Personal Protective Equipment
RDQ	Roland-Morris Disability Questionnaire
XML	Extensible Markup Language

Abstract

Project Title: Prevenir Cadas: An LHA-Based Approach to Safety Education among Latino Roofers

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The overall goal of this research was to determine the feasibility of lay health advisor (LHA)-based fall protection and prevention safety education program for Latino residential construction workers (roofers). The project included three components to address this goal. First, a formative assessment was conducted to document the beliefs and perceptions of occupational safety among Latino roofers. This formative assessment provided needed information to help insure that the LHA-based education program was linguistically and culturally appropriate. The formative assessment included in-depth interviews with 10 Latino roofers. Second, the LHA safety education program was developed. This program included a worker safety education curriculum based on a flip-chart combined with additional existing print materials. Third, the LHA safety education program was evaluated using a comparative design in which 89 Latino residential roofers were assigned to the intervention group (fall protection and prevention safety education program) or the control group (wage theft prevention program). The project's three specific aims were to: (1) develop and implement a linguistically and culturally-appropriate LHA-based safety education curriculum targeting fall prevention for immigrant Latino construction workers employed in roofing; (2) document the preliminary effectiveness in using an LHA-based safety lesson to improve fall protection and prevention safety practices among Latino roofers; and (3) identify refinements for the LHA-based safety education program to enable definitive effectiveness testing for promoting safety among Latino roofers and reducing poor occupational health outcomes.

The key findings of this project are:

- **Formative Assessment:** Participants' valued productivity over safety, and this had a negative influence on their safety behavior and reduced their PPE use. They understood that roofing was hazardous. They limited use of PPE when they felt it reduced productivity and when it was uncomfortable.
- **Baseline Data:** In the baseline interview, participants reported that the majority of employers provided PPE and that they used it most or all of the time; daily log data indicated that PPE was used for half or fewer of hours worked. 39.9% reported any injury in the last 12 months. Work safety climate was significantly correlated with the provision and use of most types of PPE, and was inversely associated with injury.
- **Intervention:** A comparison of fall safety knowledge or behavior between intervention and control participants found no significant between-group differences at baseline. At both 4 and 10 weeks after the intervention, there were still no significant between-group differences.
- **Refinements:** Latino construction workers were leery about participating in the project because they did not want to alienate their employers. The cost of using their cell phones was prohibitive. The dose of a single education session was too limited to have an effect.

Section 1. Summary

Significant (Key) Findings

This project had three aims: (1) developing and implementing a linguistically and culturally-appropriate LHA-based safety education curriculum targeting fall prevention for immigrant Latino construction workers employed in roofing; (2) documenting the preliminary effectiveness in using an LHA-based safety lesson to improve fall protection and prevention safety practices among Latino roofers; and (3) identifying refinements for the LHA-based safety education program to enable definitive effectiveness testing for promoting safety among Latino roofers and reducing poor occupational health outcomes.

Aim 1: Developing and implementing a linguistically and culturally-appropriate LHA-based safety education curriculum targeting fall prevention for immigrant Latino construction workers employed in roofing.

The formative assessment provided information needed the development of the intervention content. Participants' valued productivity over safety, and this had a negative influence on their safety behavior and reduced their PPE use. They understood that roofing was hazardous. They limited use of PPE when they felt it reduced productivity and when it was uncomfortable. Work environment characteristics that affected safety included company size, the physical demands of the job, lack of training, the need for work, general life stress, and distractions at work. An injury had to result in lost work time to be considered significant. Access to health care is limited by employers not providing Workers' compensation. Future research is needed to substantiate these descriptive results and to delineate factors that are associated with safety behavior and use of PPE. Interventions, based on a lay health educator model, are needed to improve safety in this population.

The development of the intervention produced a lay health advisor safety education program that included a lesson plan, flipchart, and additional existing materials, was developed in English and Spanish. In addition, the Computer-Assisted Telephone Surveys (CATS) software was improved to allow data to be maintained when interviews were interrupted and re-started.

Aim 2: Documenting the preliminary effectiveness in using an LHA-based safety lesson to improve fall protection and prevention safety practices among Latino roofers.

89 participants were recruited to the study and completed the baseline interviews, but only 78 completed the first week daily logs using CATS technology (72 who actually worked that week). The mean work safety climate score was 26.5 (SD=5.6). In the baseline interview, participants reported that the majority of employers provided PPE and that they used it most or all of the time; daily log data indicated that PPE was used for half or fewer of hours worked. 39.9% reported any injury in the last 12 months. Work safety climate was significantly correlated with the provision and use of most types of PPE, and was inversely associated with injury. Supervisors promoting safety may increase the PPE use and decrease injuries.

Intervention effectiveness: A comparison of intervention and control participants found: (1) no significant between-group differences in safety knowledge, and (2) no significant between-group differences in safety behavior. These null results were found at both T₁ and T₂. Some safety knowledge items and safety behaviors reported were quite high, so there was little room for improvement. However, no change was found even when individual items with low baseline

scores were reviewed.

Aim 3: Identifying refinements for the LHA-based safety education program to enable definitive effectiveness testing for promoting safety among Latino roofers and reducing poor occupational health outcomes.

Recruitment to the intervention study was difficult. Latino construction workers were leery about participating in the project because they did not want to alienate their employers. Evaluation data collection was burdensome for the participants. The amount of data collection (baseline interview, and three weeks of daily interviews) created too great a burden to the participants to want to initiate or continue participation. The Computer-Assisted Telephone Surveys (CATS) Technology used for the evaluation data collection was off-putting to the Latino construction workers. They did not like calling and providing data. The cost of using their cell phones was prohibitive; the project modified its protocol to provide some compensation for the use of cell phones. Finally, the dose of a single education session was too limited to have an effect. As a result, only 89 of the 120 proposed participants were recruited to the project, and only 67 of 100 proposed participants completed the intervention.

Translation of Findings

The key finding of this research speaks to the importance of work organization for the development of programs that educate workers and employers about occupation safety. The work organization and work safety culture for Latino construction workers limit the effectiveness of occupational safety training. For this study, workers were afraid to participate in the safety training or evaluation because they did not want to alienate their employers. Workers needed the income from their jobs and did not want to make changes that would alienate their employers. Workers indicated that they valued production and income over safety; they did not want to alienate their co-workers by slowing the crew for safety. Workers indicated that they used PPE when they perceived it to be important to their employers, even when they did not believe it made them safer. Efforts should address improving the work organization and increasing work safety culture to support of safety and PPE use. This will provide the context for providing safety training for workers.

Outcomes/Impact

This project does not have intermediate or end outcomes for worker safety and health. The results do have potential to improve worker safety and health by informing work safety training and intervention programs. First, such safety training and intervention programs must address worker values surrounding the need for employment and income which drives them to ignore safety standards that they feel limit their income. Second, safety training and intervention programs need to address worker trust. For small companies, workers are often related to their supervisors or employers; this limits their willingness to be involved in training and intervention programs. Workers' need for employment limits their willingness to participate in any research or program that may alienate employers. Third, the evaluations of safety training and interventions need to collect valid and reliable data, but also need to do so in a manner that is not too burdensome. Finally, safety training and intervention programs need to have a sufficient dose to have an effect.

Section 2. Scientific Report

Background

Construction is among the riskiest occupational sectors, and the burden of poor occupational health in construction is disproportionately borne by immigrant Latino workers. The risk of fatality within the construction industry is 40-80% higher among Latinos than non-Latino workers (Dong et al., 2004), and the risk of injury is 30% higher among Latinos (Dong et al., 2010). Illness and injury rates among construction workers are likely underestimated, especially among immigrant workers (Azaroff et al., 2002; Dong et al., 2011; Schoenfisch et al., 2010; Welch et al., 2007) who view hazards as part of the job, are intimidated from reporting injuries, or they move on to other jobs as symptoms develop, especially if they limit work activity (Brunette, 2004; Human Rights Watch, 2004; Lipscomb et al., 2005).

Educational materials and injury prevention programs are a core strategy for addressing elevated fatality, injury and illness within the construction industry (Sweeney et al., 1999). The *Fall-Safe Construction Program* (Becker et al., 2001) and the *HomeSafe Project* (Gilkey et al., 1998), for example, fundamentally rest on the ability to deliver core safety information to key stakeholders, including workers. Several projects funded through OSHA's Susan Harwood Training Grant program have developed safety materials for the growing number of Latino construction workers; many of which are simple translations of existing materials from the Construction Safety Council (Brunette, 2005). Educational materials can be effective in promoting a safer work environment and reducing injury (Becker et al., 2001; Darragh et al., 2004; Williams et al., 2010), although the rigor of formalized evaluations is suspect (Lehtola et al., 2008).

The need for high quality safety education materials delivered to immigrant workers is apparent. Fatal and nonfatal injuries are higher among immigrant construction workers (Dong et al., 2004; 2010), suggesting inadequate safety preparation. More directly, preliminary data from daily diaries using CATS technology indicated that common safety practices are not being used by Latino workers (see section 3.6 "Preliminary Studies"). For example, Latino roofers reported not adhering to one or more standard safety practices on 100% of the observed work days.

Developing effective safety materials for Latino construction workers requires several considerations (Brunette, 2005). Beyond basic issues of language and translation, developers need to recognize the low levels of formal education of many immigrant Latinos (Center for Construction Research and Training (CPWR), 2009), which raise questions about their ability to read, understand and apply content contained in safety education materials. When developing safety education materials it is important to address cultural issues like machismo, the low importance of occupational safety in many Latin American countries, and the corresponding lack of understanding of workers' rights to a safe workplace (Brunette, 2005). Further Latino construction workers report intimidation of people in power as being a barrier to requests for safety information (Menzel & Gutierrez, 2010), which may reflect a general mistrust of those in power (Brunette, 2005). This latter point, coupled with low levels of literacy, raises the key point about how educational materials can be delivered: how can materials be delivered if literacy precludes or minimizes workers' ability to obtain safety information themselves, and people in authority are mistrusted or intimidate workers?

Specific Aims

The overall goal of the proposed research was to determine the feasibility of lay health advisor (LHA)-based safety education program for Latino construction workers. LHAs provide a compelling route for delivering occupational safety content to Latino construction workers because they have been successfully used to improve occupational safety knowledge among Latino workers in agriculture (Arcury et al. 2008; Forst et al. 2004; Liebman et al. 2007; Luque et al. 2007), manufacturing (Grzywacz et al., 2009; Marín et al., 2009) and Latino day laborers in construction (Williams et al., 2010). The project aims were,

1. Developing and implementing a linguistically and culturally-appropriate LHA-based safety education curriculum targeting fall prevention for immigrant Latino construction workers employed in roofing.
2. Document the preliminary effectiveness in using an LHA-based safety lesson to improve fall protection and prevention safety practices among Latino roofers.
3. Identify refinements for the LHA-based safety education program to enable definitive effectiveness testing for promoting safety among Latino roofers and reducing poor occupational health outcomes.

Methodology

Design

This project used a combined qualitative-quantitative study design. The qualitative component of the project was designed to achieve Specific Aim 1; it was used to inform the main content and key messages of a *Falls Prevention* lesson that was created and used to educate Latino roofers in the residential construction industry about safety. The qualitative component involved conducting semi-structured in-depth interviews with up to 10 Latino roofers working in the residential construction industry.

The quantitative component of the project was designed to document achieve Specific Aim 2; it was used to document the preliminary effectiveness in using an LHA-based safety lesson to improve fall protection and prevention safety practices among Latino roofers. The evaluation of the *Falls Prevention* lesson rested on a design in which one group of Latino roofers would be randomized to receive the developed *Falls Prevention* lesson, and a second group of Latino roofers would receive an LHA-based *Wage Theft* lesson.

Setting

This was a community-based study centered in North Carolina.

Formative Assessment Component: In-depth Interviews

Sample Selection & Recruitment

We completed in-depth interviews with 10 Latino roofers working in residential construction. Inclusion criterion were: 1) self-identify as Latino, 2) currently employed 30 or more hours per week as a roofer in the residential construction industry; 3) 5 or more years of experience performing roofing in residential construction, and 4) sufficiently articulate as to clearly convey ideas and beliefs about the facilitator and barriers to advocated fall prevention practices.

Potential participants were purposefully selected to represent the range of variability in experiences as a roofer (Werner & Bernard 1994). No procedures analogous to those used in statistical research are available for choosing the optimal number of participants (sample size) in qualitative research. Based on our experience conducting research with immigrant Latino workers, we expected that a sample of 10 participants would be sufficient to identify key themes in the facilitators and barriers to advocated fall prevention practices. The goals of this component of the project were explained to the participants, they were told that they would be asked to complete an audio recorded interview, and that their participation was completely voluntary.

In-depth Interview Content

The in-depth interview content that was both general and specific to fall prevention among roofers. General information included basic background information, length of time in the roofing trade of residential construction, awareness of common injuries experienced by roofers, as well as the factors that cause those injuries. Content that was specific to fall prevention focuses on awareness of alternative strategies for injury prevention, personal beliefs about the importance of injury prevention behavior, and appraisals of peers' normative beliefs about injury and injury prevention.

Interview Procedures

Interviewers were trained in the proper conduct of conducting in-depth interviews. On meeting with a participant the interviewer obtained informed consent. The interviewer asked that the interview be conducted in a private location in which the participant could talk freely. Interviews were audio-recorded. Each interview was conducted in Spanish, the participants' preferred language.

Data Management and Analysis

Interviews were transcribed verbatim and translated into Spanish by a professional service experienced in interview transcription and translation. Data management and textual analysis used established procedures. A tracking system to manage the textual data was maintained by the Project Manager. A log of interviews was maintained to track the interviews through

collection, transcription, editing, coding and verification of codes. All transcripts will be reviewed while listening to the recordings and edited for accuracy. The mechanics of transcript coding and analysis was specific for ATLAS.ti 6.0, a computerized software package that allows coding and retrieving text.

Development of the Intervention

Development of the *Falls Prevention* LHA-based safety education curriculum included five major steps: (1) completion of the formative assessment; (2) review of existing educational materials; (3) draft of training content (“messages”) and procedures; (4) presentation of draft content and procedures to community members; and (5) revision of content and procedures.

Fall prevention was targeted because our data indicate that advocated fall prevention practices are not routinely used by workers. Materials from existing programs (e.g., *Fall-Safe Construction Program*) were reviewed and new educational tools were created to meet worker needs. Based on the formative assessment, the training program was designed to build on the knowledge that already exists among workers, and the experiences and barriers that they face when trying to work safely. The project team, representing the community organizations and other participants such as potential lay health advisors, held a series of meetings to refine and finalize the training package.

The final content of the safety education curriculum included a flipchart, “Get Smart Working in Roofing! / ¡Ponte Listo Trabajando en Roofing!” (Lane et al. 2012), supplemented with existing brochures, and a lesson-plan to support the presentation of the flipchart by the lay-health advisor.

Table 1. Participants involvement with the proposed project		
	Stage	Activity
Week 1	Recruitment	Informed Consent, Baseline Survey, 7-day diary period using CATS (T ₀)
Week 2	Randomization	Assignment to “Fall” or “Wage Theft” LHA program
Week 3	Intervention	Receipt of “Falls” or “Wage Theft” program
Week 4	Follow-up	none
Week 5	Observation	7-day diary period using CATS (T ₁)
Week 6 – 8	Follow-up	none
Week 10	Observation	7-day diary period using CATS

This project component was designed to achieve Specific Aim 2; that is, to document the preliminary effectiveness in using an LHA-based safety lesson to improve fall protection and prevention safety practices among Latino roofers. It was not intended to be a definitive test of effectiveness. The primary objective of the evaluation, therefore, was to generate preliminary estimates of the *Falls Prevention* lesson's effectiveness in promoting safety practices among immigrant Latino roofers. 89 immigrant Latino roofers in residential construction were recruited to the study and completed the baseline interview. However, only 67 of these participants actually continued in the study and received an LHA-based lesson. The sample was accrued over a 17 month period. Participants were engaged in the project for 10 weeks (Table 1) beginning with a baseline assessment and one week observation period wherein participants complete daily telephone diaries of work-related experiences, including safety behavior, using CATS technology. After the initial observation period, 37 of the recruited participants were assigned to receive the LHA-based *Falls Prevention*, the other 30 participants to receive an existing *Wage Theft* lesson. Behavior change was evaluated using data collected on two separate one-week observation periods at 5 and 10 weeks after recruitment to examine post-intervention safety behavior.

Participant selection criteria

Participants were immigrant Latino residential construction workers in North Carolina counties. The Latino population in the study counties was large, and a large proportion of Latino adults were employed in the construction industry. The inclusion criteria for the proposed study were: ≥ 18 years of age, self-identify as Latino, Hispanic, or of Latin American heritage; currently employed 30 or more hours per week as a roofer in the residential construction industry; expects continued employment as a roofer in residential construction for at least 3 months, have a working telephone (cell phone or land-line) and willing to interact with the LHA to receive education. Exclusion criteria: none.

Interventions and Interactions

Trained LHAs recruited all participants. The LHAs and Project Manager accrued a list of community sites and locations frequented by immigrant Latino residential construction workers such as tiendas (Mexican stores), labor sites, Laundromats, and churches. This list of sites was made available to the LHAs to help them find study eligible individuals. The LHAs visited identified sites, and, after obtaining permission from the site gatekeeper (e.g., pastor, tienda owner, etc.), interacted with site patrons. Once an individual had been identified as study eligible, the LHA described the study and invited the individual to participate. For those who agreed to participate, the LHA obtained informed consent and completed the baseline interview immediately. Otherwise, the LHA would schedule an appointment for the baseline interview, and obtained contact information (i.e., local and permanent address, primary and secondary telephone numbers).

A disposition sheet was completed for each contact identified as a construction worker to document acceptance and refusal rates. Basic information was collected from individuals who declined to participate, including age, gender, amount of time in the US. The disposition sheet also allowed us to determine what proportion of eligible contacts refused to participate for specific reasons (e.g., lack of interest in safe work behavior as a topic, or willingness to be trained but unwilling to participate in the evaluation).

Each study participant participated in two distinct data collection elements. The first data collection element was a baseline interviewer-administered interview implemented by the LHAs, who was trained in interview techniques. The baseline interview assessed stable attributes of the individual (e.g., age, education, country of origin, marital status), occupational characteristics (e.g., years in construction, primary tasks performed in construction, typical shift or time of day construction work is performed), and a health history (e.g., presence of chronic conditions). The baseline interview took 30 minutes to complete. Participants were given a \$15 incentive after completing the baseline interview.

The second data collection element was a one-week (7-day), end of day diary protocol. Diary data was conducted using a CATS system. The CATS system was designed and built using VoiceXML, a structured tagging language based on Extensible Markup Language (XML). VoiceXML provides basic conversational structures to implement interactive voice dialogues, such as menus, prompts and responses, and even conditionals that handle basic phone interaction states. VoiceXML prompts guided participants through a structured interview, which took approximately 15 minutes to complete. The daily interviews were conducted via telephone. Each participant was asked to complete 3, one-week observation periods using the CATS (see Table 1). Participants were given an incentive of \$20 if they complete three or more daily calls during each observation period, for a maximum incentive of \$60 (\$20 for 3 observation periods).

Participants for this study were members of a low-income, vulnerable population. They generally used cell-phone for which they paid by the minute. Therefore, for each week a participant completes the telephone interviews, the participant was given \$10 to pay for telephone costs, for a maximum of \$30 during the project.

Participants received the *Fall Prevention* safety education and training program or *Wage Theft* lesson from a trained LHA: the lesson received depended upon randomization. The lessons were delivered during the week following the first one-week observation (T_0) period using the CATS system (Table 1). The teaching methods used in both LHA-based lessons were based on the principle of active learning. Many of the participants had limited literacy. For example, over one-third (36.3%) of participants in our previous immigrant Latino construction worker project reported having less than 6 years of formal education and 78% reported less than 9 years of education, suggesting limited literacy. Therefore, training emphasized verbal presentations that invited learners to discuss the information. When appropriate, the LHA modeled behaviors and ask participants to repeat the behaviors. Participants were men; most lessons were given in a one-on-one context, and lasted 30-45 minutes. Participants received a \$20 incentive for completing the lesson.

Measures

Baseline Survey: The baseline questionnaire assessed basic demographic characteristics including age (measured in years), gender, marital status (single/unmarried, married/living as married with partner in the U.S., and married/living as married with partner in country of origin), parental status and number of dependent children (both in the U.S. and country of origin), and educational attainment (i.e., Primaria, Secundaria, Preparatoria, Universidad). Acculturation was assessed including language preference, using seven items from the Acculturation Rating

Scale for Mexican-Americans-II (ARSMA-II) (Cuéllar et al., 1995), and length of residence in the U.S. and length of residence in NC.

Occupational characteristics were assessed, including years worked in construction, primary tasks done in construction, and tenure with current employer. Bosses commitment to safety was assessed with 7 items from the Perceived Safety Climate Scale (Gillen et al., 2002). Perceived safety commitment was constructed by summing the items; higher values indicate greater perceived management commitment to worker safety ($\alpha = .74$). Safety Orientation was assessed with a single item asking, "Did you receive a site specific safety orientation before you started work?". Job design and performance variables were measured using a modified version of the Job Content Questionnaire (JCQ)(Karasek & Theorell, 1990). Responses to the JCQ were used to create measures reflecting authority, variety and psychological workload. We have used this modified instrument in our previous immigrant Latino research and have found that the reliability ranged from a low of .72 to a high of .79, suggesting good reliability (Grzywacz et al., 2007b).

Health assessments focused on musculoskeletal health. Musculoskeletal QOL was assessed with two instruments. The first was the Disabilities of the Arm, Shoulder, and Hand (DASH) questionnaire, developed to measure impairment and limitations in activities due to disorders of the upper limbs. DASH is comprised of 30 items and has been translated and validated in Spanish (Rosales et al., 2002). The second was the Roland-Morris Disability Questionnaire (RDQ), a 24-item instrument designed to measure physical disability due to low back pain. The RDQ has been translated into Spanish (Kovacs et al. 2002) and is reported to have good internal consistency (Fritz & Irrgang, 2001). Finally, health-related quality of life was measured using the Medical Outcomes Short Form-12 Health Survey, V 2.0, Acute form (Ware et al., 2000).

Measurement: CATS-Based Diary Content: The content of the diaries was designed to capture safety practices relevant to falls and factors that may affect workers' ability to practice safe practices on the job. Safety practices relevant to falls were assessed with a series of questions about behaviors performed while on the job site. Roofers share several advocated practices, including examining the job site for new fall hazards, wearing a safety harness when working at heights greater than 6', tying off ladders at the top and bottom, being secured to a tie off point, maintain three-point contact on ladders, and avoiding carrying tools and materials up ladders. Additionally, roofers are encouraged to use slide guards, mark off safety zones, verify all roof openings are covered, clear debris from walking surfaces, and not starting work if there is heavy morning dew or other slip hazards. Separate variables were created for each safety practice.

The primary outcome for determining preliminary estimates of the Fall Prevention lesson's effectiveness was change in workers' fall protection and prevention practices. Some advocated practices, like use of slide guards and not starting work even though the roof is wet are conditioned, at least in part, by the contractor or crew leader (e.g., are slide guards available to be used?). Evaluation therefore focused on changes in behavior that were less contingent on contractor or crew-chief involvement; that is, evaluation focused on changes in the number of work days in each 7-day observation period that workers reported: 1) marking off safety zones, 2) verifying the location of roof openings, and 3) clearing debris from walking surfaces.

Stressors inherent in the job were presumed to contribute to variation in safety practices, and were therefore assessed as important covariates. Therefore, the daily diary assessed several job stressors. Quantitative workload was assessed with three primary questions adapted from the JCQ, and up to three follow up probes. Job rotation was measured with a series of yes/no questions asking about different tasks within roofing or framing. Individuals reporting having performed more than one task in a workday were coded 1 for job rotation, zero otherwise. Hours spent in each task was also constructed. Several management practices were assessed. All items assessing management practices used a yes/no response option. Coercive supervision was assessed with six items adapted from the Abusive Supervision scale (Tepper, 2000). Supportive supervision was assessed with two items. Perceived commitment to safety was assessed with 4 items adapted from the Safety Climate scale (Gillen et al., 2002). Responses to each item set were summed; higher values indicate higher levels of the construct.

Analytical Plan

This randomized pilot study was designed to assess the feasibility of an LHA-based fall prevention lesson in promoting advocated safety practices among Latino roofers. Analyses obtained preliminary estimates of treatment efficacy and variability of outcome measures to inform the design of a larger-scale trial.

Evaluation of the developed LHA-based safety education program follows from our logic model (Figure 1). The evaluation documented changes in Latino roofers fall protection prevention practices in the group assigned to receive the *Falls Prevention* lesson compared to those who receive the *Wage Theft* lesson, both delivered by a trained LHA (specific aim 2), and identify refinements for the LHA-based safety education program to enable definitive effectiveness testing for promoting safety among Latino construction workers and reducing poor occupational health outcomes (specific aim 3).

Analysis. All analyses were performed using SAS v9.2 (SAS Institute, Cary, NC). Descriptive statistics were presented as frequency and percentage for categorical variables and mean $\pm$ standard deviation or median and inter-quartile range for continuous measures. All randomized participants were included in the analyses.

The 95% confidence intervals were provided for estimates of effect size and standard deviation. Baseline characteristics were compared between two treatment groups to ensure balance by randomization. Mixed effects models with three time points – baseline, 5 weeks, and 10 weeks and an unstructured dependence structure were fitted to test treatment effect. Summary statistics were derived from week long observation and used as outcomes in mixed effects models. Covariates adjusted in the models include selective demographic characteristics. The type I error rate was fixed at 5%.

Process Evaluation. Data from multiple perspectives were collected throughout the 17-month recruitment and training period to determine potential targets for program refinement (Specific Aim #3). LHAs kept detailed notes of each interaction with all study participants. The project manager and the field supervisor maintained detailed notes about each LHA based upon their

weekly meetings. Collected information was summarized to identify program strengths and opportunities. Collected information was used to identify additional refinements to the *Falls Prevention* safety education program, including possible refinements to the content contained in the developed program materials, or possible changes in the way LHAs could better deliver the content (see feedback loops in Figure 1). Additional considerations relevant to “scaling up” the LHA-based safety education program (e.g., field supervision, LHA workload) were evaluated.

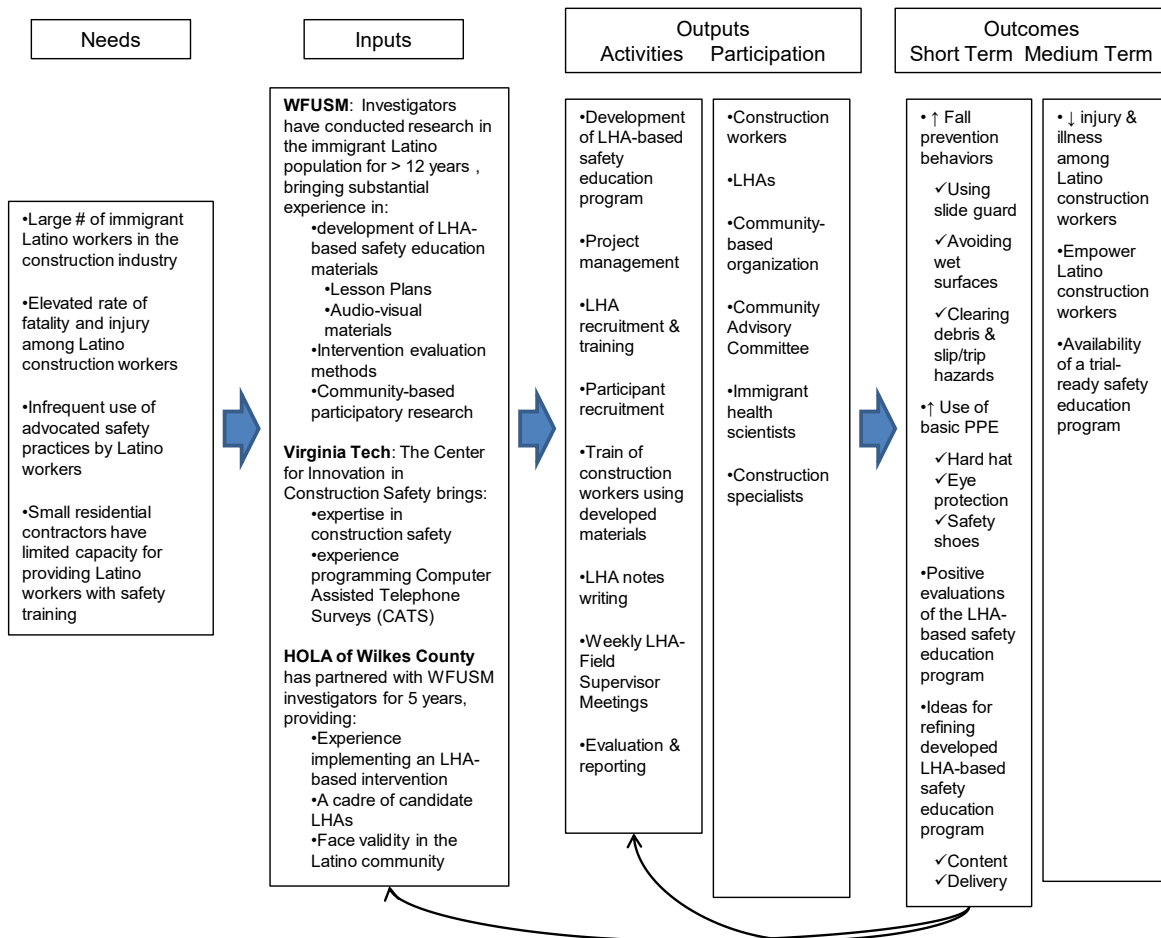


Figure 1. Logic model guiding evaluation of developed LHA-based safety education program.

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Project Results

1. Occupational Safety Beliefs among Latino Residential Roofing Workers

Abstract

Background This analysis describes beliefs about work safety and personal protective equipment (PPE) among Latino roofing workers, it delineates their perceptions of work environment characteristics that affect work safety and PPE use, and it describes how they experience work injuries and the consequences of these injuries.

Methods In-depth interviews were completed with 10 current and former Latino residential roofers. Interview transcripts were subjected to systematic qualitative analysis.

Results Participants' valued productivity over safety, and this had a negative influence on their safety behavior and reduced their PPE use. They understood that roofing was hazardous. They limited use of PPE when they felt it reduced productivity and when it was uncomfortable. Work environment characteristics that affected safety included company size, the physical demands of the job, lack of training, the need for work, general life stress, and distractions at work. An injury had to result in lost work time to be considered significant. Access to health care is limited by employers not providing Workers' compensation.

Discussion Future research is needed to substantiate these descriptive results and to delineate factors that are associated with safety behavior and use of PPE. Interventions, based on a lay health educator model, are needed to improve safety in this population. Safety regulations need to be evaluated and their enforcement needs to be improved.

Introduction

Latinos working in residential roofing experience high rates of injury. Latino and foreign born construction workers suffer injury and death due to falls from roofs at greater rates than do non-Latino and native born workers (Dong et al., 2009, 2013). Greater fatality rates from roof falls are also associated with employment by small establishments (1 to 10 employees) (Dong et al., 2013). While occupational injuries in construction on the whole are on the decline, work-related deaths among Latino construction workers have risen by one third (Dong et al., 2010a, 2010b). A major concern within the construction industry is eroded safety practices such as "cutting corners" relative to safety and health training and safety equipment installation and usage (Dong et al., 2009).

Latino construction workers are typically young, speak only Spanish, have little formal

education, and are employed in low-skill, high-risk occupations (Dong et al., 2009). These workers face enormous pressure to work quickly on the jobsite due to their need for employment, perceptions that employers view workers as disposable, and fear of retaliation if they complain about conditions (Roelofs et al., 2011). Like Latino workers in other industries (Arcury et al., 2012a; Keifer et al., 2009; Grzywacz et al., 2007; Quandt et al., 2006), Latino construction workers are willing to tolerate unsafe conditions due to these pressures (Menzel & Gutierrez, 2010; Roelofs et al., 2011). Latino roofers have less perceived control over their personal safety than others in the construction trades, and they have lower perceived work safety climate (the perception of supervisor's value of safety relative to production) than other Latino construction workers (Arcury et al., 2012b).

Although Latino roofers have high rates of occupational injuries and they believe they have a poor safety climate at work, little is known about their perspectives and beliefs regarding occupational safety and injuries. The fall-protection training needs of Latino roofers have been documented, as have the format in which training is desired and the barriers to providing this training (Hung et al., 2013). Hung and colleagues (2013) reported that the "safety status quo" among Latino roofers is perpetuated by workers' perception that they already know about safety, and that the workers do not value work safety due to their overconfidence. Hung et al. (2013) used a quasi-qualitative approach to document worker preferences, but it was limited as results from American and Latino workers were mixed and all data were collected at the worksite during lunch breaks. Actual beliefs about the importance of training and the on-the-job experiences of Latino roofing workers have not been documented.

This analysis uses a qualitative research design to address three aims. First, it describes beliefs about work safety and personal protective equipment among Latino roofing workers. Second, it delineates Latino roofer perceptions of work environment characteristics that affect work safety and use of personal protective equipment. Finally, it describes how Latino roofers experience work injuries and the consequences of these injuries.

Methods

Sample

Ten Latino immigrant construction workers were recruited to participate in this study in 2011. Participants were recruited from communities in western North Carolina. A single interviewer worked with a local organization serving the Latino community to recruit participants. Members of this organization identified individuals currently or recently employed as roofers. The interviewer contacted identified individuals, explained the project, and answered any questions that they had. Participants were purposively selected to represent a range in ages and experience with roofing, with some of the roofers being crew leaders. The participants had a range of experience in roofing, but all had recent experience in residential roofing. The information provided by participants was used in the design of a fall prevention education program (Lane et al., 2012). The study protocol was reviewed and approved by the Wake Forest School of Medicine Institutional Review Board. Participants provided signed informed consent.

Data Collection Methods

Each participant was interviewed individually, and each was assured that all information shared would remain confidential. Interviews were conducted in Spanish and lasted about an hour. The interview guide consisted of sections aimed at learning more about workers' perceptions about work safety. These sections included: basic information, risks of injuries in construction, usage of personal protection equipment, work safety, and safety training and regulations. All interviews were audio-recorded.

Data Analysis Methods

Recorded interviews were transcribed and translated to English. Each translation was checked against the original recording for accuracy. The investigators reviewed each transcript and developed a list of themes based on this review. The investigators discussed the themes and agreed about the salience of each. Saliency analysis assesses thematic patterns across all of the interviews by evaluating recurrent themes based upon their frequency of occurrence, the participants' emphasis on the themes, or descriptive capacity of the theme recognized by the research team (Arcury et al., 2001; Buetow, 2010). A salient theme may not have been discussed by every participant, but it was discussed in detail and with emphasis throughout the sample or it was found to provide insight or explanation of a given phenomenon. Through this iterative process, quotations that demonstrated the understanding of hazards and safety among Latino roofers were identified and analyzed.

Results

Participant Characteristics

All participants were native Spanish speakers with limited English language skills. Their ages ranged from 22 to 44 years old. Participants had been working in the United States for 10.5 years, on average. Seven participants had children. Eight participants were currently employed in roofing, and two had recently been employed in roofing. Eight participants worked predominantly with asphalt shingles, and two participants worked predominantly with metal roofing.

Beliefs about Work Safety and Personal Protective Equipment

Participants discussed a consistent set of beliefs about work safety and about the use of personal protective equipment (PPE). A general belief underlying views of work safety and PPE use was the expectation that all members of the work group should work equally and that all group members should work at the pace set by the group. One described his crew's value, "We get tired of seeing people who are lazy or aren't giving it their all" (Interview 2). Participants wanted to complete each roof as quickly as possible so that they could move on to the next job. This mindset of working quickly was the dominant reason participants gave for not using PPE.

Beliefs about work safety: Participants agreed that roofing was hard and strenuous work in which the risk of injury was ever present. The occupational risks in roofing were believed to be inherent, and participants were aware of safety hazards related to working at heights. The most strenuous activity was getting the roofing materials up a ladder onto the roof. Working at heights was the most risky part of the job. They discussed different coping mechanisms for dealing with the risks associated with the heights at which they work. Some tried to minimize these risks by posturing as if risks were normal and unavoidable, while others discussed precautions such as the use of PPE.

The participants were aware that American workers perceived safety differently. They understood that American workers took their time to use PPE and did not work as fast as Latino roofers. One participant stated that the work culture in Mexico predisposed Mexican workers to not value safety precautions. Experience was seen as the best guide for safety. Roofers drew on their own experience when making appraisals of the safety risks related to a particular job. Roofers determined the level of risk posed by a job site by eyeing the pitch of the roof and evaluating potential sources of slip hazards (e.g., snow), and then made decisions about action based on these evaluations (e.g., waiting for snow to melt).

Beliefs about PPE: The roofers had a common perception that using PPE was a cost both in purchasing and in reducing their productivity. They also stated that PPE was often uncomfortable and actually increased their risk.

Participants saw the use of PPE as a luxury and felt that the costs of using PPE outweighed the benefits of its protection. The beliefs about the purchasing and productivity costs of PPE are interwoven: “Because we have to buy (boots). The boots used on roofs are specially made for that, but they’re expensive” (Interview 10). Cost was also affected by who bore the responsibility to provide the PPE. One crew leader vented his frustration at having to continually replenish PPE, “I’d like to tell them to buy their own equipment, but they aren’t going to want to spend that much money. They can’t fathom spending \$250 when that’s as much as they make in a week. If their employer doesn’t provide it to them, then, there isn’t a way that I can get them to buy it” (Interview 8).

Many roofers shared the perspective that, “Without protection and gloves, you can work faster” (Interview 3). Workers perceived PPE as an encumbrance on their time, translating into lost productivity. One roofer tried to encapsulate this concept in stating how workers were caught in the middle of this tension between safety and productivity.

It’s because our boss, for example, doesn’t have the money to buy those things. So, that’s something that makes us not use them. Slide guards should be used for our safety. However, they cost money. They could buy them, but you have to take time to install them on the roof that you’re about to work on. The time you take to do that makes our boss lose money. (Interview 7)

The workers had very little tolerance for safety measures if they felt like they were back up measures for other PPE. They did not appreciate redundant PPE. This redundancy was viewed as an even greater cost due to set up time and purchase price.

In the type of work we do, we don't have the privilege of using (harnesses) because you need to make money. Thankfully, where I'm working, the roofing market hasn't been devalued that much. But there are places where roofing companies pay an average of \$20 a bundle. When it's like that, you don't have the privilege of wasting time putting up slide guards to stay safe when you don't need them because what slide-guards do is serve as a backup for the rope and harness. (Interview 9)

Because of the complex nature of this cost-benefit approach to safety, many roofers improvised PPE, creating innovative solutions to PPE provision that fit their values. One described a rope system as a work around for a harness system because they needed to be able to "move around." Others were aware of how their improvised approach fell short of the design standards of PPE that was found in the marketplace.

Participants reported that discomfort was another barrier to PPE use. The concept of comfort and the perceived risks that come with wearing PPE were closely linked. These concerns included PPE restricting movement, becoming tangled, being heavy, and impeding communication. Participants believed that restrictions in range of movement were hazards. Many felt less safe wearing PPE because it made their movement awkward. Without PPE they felt more agile and balanced. The effort required to coordinate the various workers who were on a roof and harnessed was perceived as a tangle hazard and waste of time. This constant demand to adjust the PPE was a barrier.

It's uncomfortable and heavy. Plus, we also have to be tied to the ropes, which are thick. And if we're working in this area, we have to climb up, which makes us have to constantly move the ropes. (Interview 2)

One participant reported that hearing protection was a hazard because it impeded communication: "The thing that makes us the maddest is when they wear their earplugs and can't hear us" (Interview 4).

When PPE was not fully provided, the use of certain parts was uncomfortable and gave only the illusion of safety. One participant made this point clear from his experience with improperly provided PPE.

The rope we use to tie things with. The rope isn't in good condition all the time. . . . So, jobs force us to tether properly, but it's hard to do because the ropes aren't any good. . . . We work un-tethered a lot because we don't have the anchors. So, the harness and the ropes just become an annoyance because we don't have the anchors. . . . So, most

of the time, it's lack of proper equipment . . . because it doesn't do me any good to wear a harness when I don't have a good rope or an anchor. All it would do is make me uncomfortable as I work. It would bother me. (Interview 1)

Participants reported that some workers teased and made fun of those who chose to use PPE. Teasing centered on the accusation of being scared, a threat to their masculinity, and looking different from their peers. Not being "scared" was a valued trait that was demonstrated in not using PPE. This participant's perspective on roofing was that the work was very masculine; "They tell you that you're a woman (*senorita*) if you're wearing that on the roof, things like (a harness)" (Interview 10). The participants said that teasing happened when people stuck out or looked different. Some participants reported enduring this ridicule because they felt their safety was more important than their coworkers' assessment of risk.

(I use PPE) because I'm interested in staying alive and taking care of myself. I don't want to have an accident and go back to Mexico missing an arm or a finger, or having a bum leg, or being blind in one eye. I want my family to have me back healthy like I was when I came here. (Interview 5)

The general sense among the participants was they would wear PPE if it was a condition of employment: if an employer provided and required PPE, then they would use it. This system is reinforced with the threat of not working if caught without PPE, "Yes, (the supervisor) tells us that the first person who doesn't have it on will be sent home for two weeks because they need to use it. That makes us decide that we should wear it" (Interview 4).

Work Environment Characteristics that Affect Work Safety and PPE Use

Participant discussions indicated several salient factors that affected work safety and PPE use. These included the size of the company that employed them, the physical demands of the job, lack of training, their need for work, general life stress, and distractions at work.

Company size: The size of the construction company affected safety measures. Larger companies had more supervision and enforced safety measures. Participants discussed their experiences working for different companies to make comparisons with their current environments. Larger companies were more likely to have safety training. Smaller companies and "individuals" did not operate at the same level of risk prevention.

Physical demands of the job: The physical demands of roofing work were perceived to be a source of work safety risk. These physical demands included carrying heavy loads, working at heights, climbing ladders, and navigating housing structures. Participants stated that carrying the bundles of shingles up a ladder was a constant hazard that they faced. They referred to this task as the heavy work of roofing. Working at heights presented fall risks. Ladder stability and age of ladders was a concern. "There are people who don't use the proper

equipment (ladders) and want to do the job with magic” (Interview 9). Physical demands also came from the structure being roofed; this included the structure having rotted areas and areas that would not bear up under the weight of the work, as well as the pitch of the roof.

Lack of training: The roofers reported receiving little formal training in work safety. Their perspective on training was that experience was the best teacher, that they already knew the necessary information, and that illiteracy was a possible barrier to formal training. Experience in the industry was believed to be the best way to learn about work safety. Participants who had been injured on the job reported using more safety measures, such as hardhats and harnesses; in response to a question about wearing a hardhat, a participant responded, “Yes, but I went and put it on after I got hit” (Interview 10). Participants reported a gradual learning process that often had new roofers start out doing clean up on the grounds as an orientation before they got onto the roof. The general sense was that safety hazards were so obvious that anyone should know how to avoid them. Therefore, they did not need further work safety training. Further, many roofers have little formal education; and illiteracy was a barrier to work safety training based on written materials.

Need for work: The need for work resulted in several types of stressors. These included the fear of reprisal from employers if any safety concessions were requested, willingness to be subjected to hazards for the benefit of gainful employment, pressure to work to fulfill family obligations, and the demands inherent with piece work compensation. Having stable work was highly prized among the participants. Consistent work was one of the main reasons they remained in the industry, and one of the reasons they did not complain when injuries occurred. They reported being “afraid” to make requests of employers because they wanted to keep their jobs. When asked about the difficult working conditions, one respondent stated, “It doesn’t matter what conditions I’m faced with, I still have to support my children. That’s how the majority of Latinos are. Even if the work is hard, we do it anyway” (Interview 2). Participants felt the need to work fast to secure more work because more work resulted greater job stability. This was true of those paid by the roof and those paid by the hour.

General life stress: The participants reported that general life stress that they experienced was a distraction that increased their risk of injury at work. Life stressors included poverty, work pressure, and personal problems: “Sometimes it can be family problems or problems somewhere else. It can also be a problem if they haven’t been working a lot” (Interview 6).

Distractions at work: Participants discussed several sources of general distractions that increase the risk of injury at work. These include coworkers who came to work with hangovers, and the use of cell phones when on the roof. “I think that everyone has some sort of distraction at work. You could be distracted due to stress, a personal problem, or by thinking you can’t last until break time. You’re forced to keep working. They could be on their cell phone at work” (Interview 9).

The Experience of Work Injuries and Their Consequences

How Latino roofers experienced work injuries includes their definitions of such injuries and the injuries that they commonly experienced. The consequences of these injuries include beliefs about their access to medical care.

Definition of a work related injury: Only occurrences that physically prohibited an individual from working were defined as injuries. Events that did not limit the ability to work were considered to be just part of the job and not real injuries. Participants understood that loss of work time due to an injury meant loss of wages and a financial setback. Most saw themselves as personally responsible for their injuries at work, saying that if they were injured, it was their own fault for being distracted or simply making a mistake. Similarly, participants blamed workers who experienced an injury: "I think it was because he was stupid, since anyone can cut something with a knife" (Interview 4).

Commonly experience injuries: Common injuries enumerated by the participants were puncture wounds from nails, being struck by a falling object, muscle strain, falls from heights, and cuts. Four recounted stories of falls. All reported being cut by either shingles or metal roofing materials. Two discussed muscle strains. Most had experienced with some repetitive motion pain.

We've had occasions when a nail has gone in someone's foot. It doesn't matter if you're wearing boots because they can poke you through the bottom. Other people and I have had nails stab our feet. The nails get exposed when we're tearing down. We have to remove the nails ourselves and we can step on them. It doesn't matter if you're wearing boots, even if they're good or special boots because if you step on a nail, it will go through them. (Interview 2)

Access to care: Participants indicated that little health benefit was provided to workers who experienced work injuries, including through the Workers' Compensation system. One participant said "Because as workers, we're afraid that if we ask them to do that or if we ask them to help us and pay us that money, when we get better, they aren't going to give us our job back" (Interview 1). A few said that not having Workers' Compensation was part of the terms of employment. Specifically, their prospective employers told them that they would not provide Workers' Compensation; workers who wanted Workers' Compensation would not be hired. One participant reported that at the hospital he denied that his injury was work related to protect his employer.

You might get a ride to the hospital where they leave you. That's all that happens. They leave you there so you can be seen, but we're the ones who get the bills. I've been injured when we're nailing, and it was one of the first times that I wasn't using glasses. The nail hit and shot dirt into my eye. I've had that happen to me twice. That's why I started using glasses. So, that was very expensive for me. It came out to be \$7,000 or \$8,000. My employers asked me why I didn't use glasses, and I told them that it was because they didn't give me any. (Interview 8)

Consequence of injury: Participants understood that loss of work time due to an injury meant loss of wages and a financial setback. Some employers provided some pay during the days that an injured employee missed work, though the majority did not. If participants did not work, they were not provided any benefits or compensation even though lost work was due to a work related injury. Several were confused about whether undocumented workers qualified for Workers' Compensation. Because of the consequences of injuries and personal experience, a few of the workers had embraced PPE.

My main goal is for me to stay safe. If I listen to them and end up falling and hurting myself, they aren't going to help me with my bills. They aren't going to have time to go help me at home and see what I need. If you fall, they send you home; and you have to fix it yourself. So, why would I injury myself if I can avoid it? It's smarter to protect yourself than not to. (Interview 7)

A crew leader had a different perspective that included shared responsibility among all involved in a workplace injury.

My paying for the medicine or taking them to the doctor, if they cut themselves and have to have stitches: I take responsibility for that and for the time he's out of work. I provide some sort of compensation. If you can negotiate that between the worker and the employer, it's good because you maintain a trustful relationship. There are also people who are irrational. They fall when they aren't being careful and want more compensation. (Interview 9)

Discussion

This analysis delineates the occupational safety experiences of Latino residential construction roofers and the factors that affect their work safety and use of PPE. Although conducted to inform the development of a safety training program to prevent falls among Latino roofers (Lane et al., 2012), it provides information that can be used to address safety training for the array of hazards that Latino residential roofers encounter. Participant discussions provide new insight into how small residential roofing contractors circumvent safety and compensation regulations, thus increasing the risks for occupational injuries and allowing the individual worker to assume the cost of injury. Workers have an accurate understanding of the barriers to safety training (Hung et al., 2013), and they understand that non-Latino workers follow safety procedures and use PPE more often than they do. They believe that safety training is of limited value and that job experience is the best source of safety information (Hung et al., 2013). The work organization attributes of these vulnerable workers suggest a social ecological approach for addressing the occupational health inequities they experience (Baron et al., 2013); research and intervention to improve safety for these vulnerable workers should consider individual, work crew, employer, and regulatory factors.

The participants in this study share the attributes reported for other Latino manual workers (Arcury et al., 2012a, 2012b; Keifer et al., 2009; Grzywacz et al., 2007; Quandt et al., 2006). They fear job loss and they value work and productivity over safety; they believe that this is necessary so that they can take care of their families. A common worldview among immigrant Latino workers, whether or not they are documented, is the desire not to interact with anyone who might represent the government, including safety inspectors and health officials, due to past discrimination and the fear of deportation (Arcury & Quandt 2007; Arcury et al. 2010). They also believe that, as men, they should accept occupational hazards and act as if they cannot be harmed by exposure to these hazards. These are vulnerable workers who have little control of safety in the work environment, who have few resources, and who, when injured, are at financial risk (Arcury et al. 2012b).

Occupational safety training targeting these workers is needed (Hung et al., 2013); these workers also need basic information on occupational safety regulations and their rights as employees in the US. For example, they need to know that they have a right to Workers' Compensation and that all safety regulations apply to them, whether or not they have documents. This training is needed to prevent injuries of all types, including those resulting from falls, from sharp tools, and from carrying heavy loads. It is also needed to support these workers when they are being treated for occupational injuries so that they know their rights to receive medical care and rehabilitation. Those providing this training should have the characteristics that make them acceptable and credible to Latino construction workers. Lay health educators and peer-led participatory health and safety training have been shown to be appropriate for this population (Williams et al., 2010; Ochsner et al., 2012; Lane et al., 2012); these lay health educator models have worked with other Latino worker populations (Grzywacz et al., 2009; Marín et al., 2009; Quandt et al., 2001).

Enforcement and evaluation of current safety and insurance regulations are needed. The Occupational Health and Safety Administration expanded fall protection standards for residential construction in 2012 (https://www.osha.gov/doc/residential_fall_protection/ppt/index.html). However, making the standard effective will require sufficient resources to enforce it and an improvement of work safety culture among Latino roofers and their employers (Arcury et al., 2012a). Workers admit that they use of PPE and adherence to safety procedures is required when they are working for larger employers who demand use of PPE and safety. Employers, who deny they are responsible for providing Workers' Compensation, because workers are "contractors" and not employees, are dishonest. Employers not providing appropriate PPE, encouraging their employee to ignore safety procedures to increase productivity, and not providing insurance that pays for worker injuries are responsible for the greater injury rates among the employees of small construction businesses (Kaskutas et al., 2009; Sa et al., 2009; Smith-Jackson et al., 2011; Grzywacz et al., 2012; Dong et al., 2013; Lipscomb et al., 2013). Efforts need to focus on small contractors, particularly those that employ non-union workers (Ruttenberg & Lazo, 2004). If Workers' Compensation regulations are applied equally across all employers, none will have a competitive advantage.

This analysis should be considered in light of its limitation. It is based on a small, non-random sample recruited from one area of one southern state; therefore, its results may not be generalizable. It also does not include specific measures of injuries experienced by the participants.

Conclusion

Latino construction workers are proud of their work ethic, enjoy the camaraderie of the roofing crew, and enjoy working outdoors rather than being “cooped-up.” However, due to the hazards of this work, they would leave roofing if a better opportunity presented itself. Additional research is needed to document the patterns delineated in this descriptive analysis in a larger sample of Latino roofers. Such research should consider measures from different levels of the social ecological mode (individual, work crew, employer, regulatory) in defining the factors that can be addressed in reducing occupational injuries in this population (Baron et al., 2013). Efforts are needed to develop and implement safety training programs for these workers; such programs should include information on employer responsibilities and the rights of all workers to pursue grievances when employers are not meeting their responsibilities. They need to be culturally and educationally appropriate (Arcury et al., 2010). Training programs based on lay health educator models (Williams et al., 2010; Ochsner et al., 2012) and social marketing (Menzel & Shrestha, 2012) that have been implemented with Latino construction workers are examples of such culturally appropriate programs. Such programs are needed in more areas of the country, but they should be evaluated to demonstrate the key factors that will improve occupational safety behaviors in this population.

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2. Work Safety Climate, Personal Protection Use, and Injuries among Latino Residential Roofers

Abstract

Background: This analysis describes work safety climate, PPE use, and injuries among Latino residential roofers, and examines the associations of work safety climate with PPE use and injuries.

Methods: 89 North Carolina residential roofers completed a baseline interview and daily logs about perceptions and use of PPE, occurrence of injuries in last 12 months, and work safety climate.

Results: The mean work safety climate score was 26.5 (SD=5.6). In the baseline interview, participants reported that the majority of employers provided PPE and that they used it most or all of the time; daily log data indicated that PPE was used for half or fewer of hours worked. 39.9% reported any injury in the last 12 months. Work safety climate was significantly correlated with the provision and use of most types of PPE, and was inversely associated with injury.

Conclusions: Supervisors promoting safety may increase the PPE use and decrease injuries.

Introduction

Construction workers experience high rates of injury and fatality (Bureau of Labor Statistics, 2012). Rates of injury and fatality are greater among immigrant and Latino construction workers than among native and non-Hispanic white construction workers (Dong & Platner, 2004; Center for Construction Research and Training, 2013). Roofers are particularly susceptible to injury and fatality, particularly from falls (Bureau of Labor Statistics, 2010).

Latino immigrant workers are a vulnerable population. Latino construction workers are typically young, speak Spanish, have little formal education, and are employed in low-skill, high-risk occupations (Dong et al. 2009). However, research on risk factors for occupational injuries among Latino construction workers, including residential roofers, is limited. Menzel and colleagues (Menzel & Gutierrez, 2010; Menzel & Shrestha, 2012) and Roelofs and colleagues (2011) have examined safety issues among general Latino construction workers using qualitative methods. They report that Latino construction workers are willing to tolerate unsafe conditions and to work quickly due to their need for employment, their perceptions that employers feel workers are disposable, and their fear of retaliation if they complain about unsafe conditions. These are beliefs that the Latino construction workers share with immigrant workers in other industries (Arcury et al., 2012a; Keifer et al., 2009; Grzywacz et al., 2007; Quandt et al., 2006). Two qualitative studies have focused on the safety beliefs of Latino residential roofers. Hung and colleagues (2013) examine beliefs about fall-prevention training and report that the “safety status quo” among Latino roofers is perpetuated by workers’ perception that they already know about safety, and that the workers do not value working safely due to their overconfidence. Arcury and colleagues (2014) discuss the value that Latino roofers place on productivity over safety. This differential value of productivity results in less use of personal protective equipment (PPE) and greater unsafe behaviors when PPE use and safe behaviors are perceived to lessen productivity

Work safety climate, worker perceptions of how much their supervisors value safety over

production (Zohar, 1980), is particularly important for the safety of immigrant Latino construction workers. Positive safety climate is associated with occupational safety performance and reduced occupational injuries (Neal & Griffin, 2002; Zohar, 2010). Work safety climate is related to work demands, and to the frequency and severity of injuries among construction workers (Choudhry et al., 2007, 2009; Gillen et al., 2002; Shoji & Egawa, 2006). Immigrant Latino construction workers' beliefs about the importance of high productivity to maintain employment and about the importance of loyalty to supervisors (Arcury et al., 2014), together with the understanding that men should accept risk (Arcury et al., 2012b), indicates that their evaluation of the value a supervisor places on safety will strongly influence their behavior. Arcury and colleagues (2012) examine the associations of work safety climate with safety practices among Latino residential construction workers from three trades, including roofers. Roofers reported the worst work safety climate; for all of the Latino construction workers, work safety climate was positively associated with safety practices.

Although they constitute a large part of the construction industry and experience high rates of injury, few research data exist on Latino construction workers in specific trades. The aims for this analysis are to describe the perceived work safety climate among Latino residential roofers working in North Carolina, to describe the perceptions and use of PPE among these roofers, and examine the associations of perceived work safety climate with perceptions and use of PPE and experience of injuries among these roofers.

Methods

The data for this study were collected as baseline information for the test of an educational intervention to improve fall safety among Latino residential roofers (Lane et al., 2012). The project was approved by the Wake Forest School of Medicine IRB, and all participants provided signed informed consent.

Participant Recruitment

Participants for this study were required to be aged 18 years or older, self-identified as Latino or Hispanic, currently employed 30 or more hours per week as a roofer in the residential construction industry, expected to continue employment as a roofer in residential construction for at least 3 months, and have a working telephone (cell phone or land-line). No lists of Latino roofers or the companies that employ them exist. Several procedures were used to identify and recruit participants. First, project staff used their personal networks and familiarity with the Latino community to identify individuals who they thought met the inclusion criteria. Second, project staff contacted local organizations serving the Latino community and asked organization staff to identify individuals who met the inclusion criteria. Finally, project staff generated a list of community sites and locations frequented by immigrant Latino residential construction workers such as tiendas (Mexican stores), labor sites, laundromats, and churches. Project staff visited these sites and asked the site managers and patrons to identify themselves or others who met the inclusion criteria. Of those who met the inclusion criteria, 89 agreed to participate and 26 declined, for a participation rate of 77%. The actual participation rate may be lower as individuals not wanting to participate could have avoided project staff. The common reasons given for declining participation were that the intervention would require too much time; the intervention would require high telephone charges; and fear of offending their employers. When an individual agreed to participate, project staff reviewed the intervention and data collection program with the participant, answered any questions, and obtained informed consent.

Data collection

Two procedures were used to collect the data used in this analysis. First, participants completed an interviewer-administered questionnaire that addressed participant personal and work characteristics, work safety climate, whether PPE was provided and used, and occupational injuries experienced in the previous 12 months. The questionnaire was completed at the time the participant gave informed consent. Interviewers were fluent Spanish speakers who were trained by the investigators. Second, the participants completed a series of daily logs using interactive voice response (IVR) technology (Abu-Hasaballah et al., 2007; Grzywacz et al., 2014). IVR technology uses stored, pre-recorded questions or Voice Extensible Markup Language to deliver audible questions to study participants over the telephone. Participants respond to questions by entering a number as a text response on their telephone's keypad or by responding verbally. Participants completed daily logs for a period of up to seven days after the baseline interview. The daily logs provided information on the percent of working days the participant used specific types of PPE. Participants received an incentive of \$15 for completing the baseline interview, and an incentive of \$20 plus \$10 for telephone costs for completing the daily logs.

Measures

Personal and work characteristics were based on items in the baseline questionnaire. They included age in years, years lived in the United States, years lived in North Carolina, years of education, years working as roofer, weeks in the last year working as a roofer, and hours per week in the last year working as a roofer. Other items addressed country of origin (Mexico or other), language spoken as a child (Spanish or indigenous), pay schedule (hour, day, week, or roof), and number of contractors worked for in past year (one, more than one). Finally, participants indicated if they had ever received formal training in roofing, roofing safety, or ladder safety.

Work safety climate was evaluated with the 10-item scale developed by Gillen and colleagues (2002). Nine of the items in this scale used a four-point Likert format (strongly agree, agree, disagree, strongly disagree). The tenth item included three response categories. Values for the scale ranged from 9 to 39, with higher values indicating better work safety climate. The mean score in this study was 26.5, with a standard deviation of 5.6 ($\alpha = 0.73$). The Spanish translation of this scale has been used in several previous analyses with workers in construction, manufacturing and agriculture (Arcury et al., 2012a; 2012b; 2013).

Two sets of PPE use measures are based on items collected in the baseline interviews and used in previous research with Latino construction workers (Grzywacz et al., 2012a). For the items eye protection, hearing protection, cut-resistant gloves, abrasion-resistant gloves, hard hat and harness, participants reported whether it was provided by their employer (yes/no) and if they used it none/some of the time versus most/all of the time. Two other sets of PPE measures are based on items collected in the daily logs. For the items eye protection, hearing protection, gloves, hard hat and harness, participants reported if they believe their use was not important versus important. These measures were based on a set of true-false statements in which participants were asked to judge the overall value of each item (e.g., "Hard hats are not really needed for roofers;" "It is important for Roofers to wear safety glasses while working."). They also reported the hours they wore the items; based on the hours worked for the days they completed the daily logs and the hours they reported wearing the item, the percent of time used was calculated for each item.

Participants reported whether they had sustained each of a set of injuries in the previous

12 months in the baseline interview. A series of dichotomous measures was constructed from these responses. These measures included, first, whether participants had experienced a fall while working in roofing or an electrical shock. Second, these measures included whether participants had experienced a cut or laceration, bruise or contusion, strain or sprain, flame or chemical burn, head injury like a concussion or knocked unconscious, dislocated joint, broken or fractured bone, electrical shock, or any other injury. A measure of Any Injury was recreated based on the occurrence of any of the specific injuries.

Analysis

Summary statistics (means, standard deviations, and percentages) are used to describe participant characteristics, work safety climate, use of personal protective equipment, and injuries during the previous year. The association between the work safety climate score and PPE use was evaluated using Spearman correlation coefficients. T-tests were used to compare the work safety climate score among those with and without injuries. All tests were considered significant at $\alpha < .05$.

Results

Participant Personal and Work Characteristics

All participants were male. They had a mean age of 34.6 years, and had lived in the US for an average of 12.6 years and in North Carolina for an average of 9.9 years (Table I). They had an average of 8.2 years of education. They had worked in roofing an average of 7.4 years, and worked an average of 38.6 weeks in roofing in the past year and had worked an average of 39.1 hours per week. Most (85.3%) participants were from Mexico, and the first language for most (95.5%) was Spanish. Most (85.3%) were paid by the hour, and most (82.1%) had worked for the same contractor in past year. The majority of participants had ever received training in roofing (58.4%), roofing safety (60.7%), and ladder safety (68.5%); this indicates that 30% to 40% of the participants had never received safety training for their work in roofing.

Perceived Work Safety Climate

The measure work safety climate score was 26.5 with a standard deviation of 5.6 (Table II). Several of the items indicate a lack of perceived work safety climate. Little more than half (53.9%) of participants indicated they agreed or strongly agreed with the statement that they were regularly praised for safe conduct, and about half (52.8%) indicated they agreed or strongly agreed with the statement that they received safety instructions when hired. Fewer than one-third (29.2%) stated they agreed or strongly agreed with the statement that taking risks was not part of their job, and 83.1% agreed or strongly agreed with the statement that it was very likely that they would be injured in the next 12 months. Finally, 20.5% stated that their supervisors were doing as much possible to make the job safe.

PPE Use and Beliefs

Many of the participants reported that PPE was provided for them (Table III). Most (65.9%) were provided with eye protection, many (40.2%) were provided with hearing protection, and most were provided with cut-resistant (59.3%) and abrasion-resistant (54.7%) gloves. Almost all were provided by their employers with hard hats (81.4%) and harnesses (93.0%). With one exception, the majority of participants reported that they used each type of

PPE most or all of the time. Most reported using eye protection (68.5%), cut-resistant gloves (62.9%), abrasion-resistant gloves (65.2%), hard hats (71.6%), and harnesses (57.3%) most or all of the time. Hearing protection was used by 28.1% of the participants most or all of the time.

Based on the daily logs, participants actually used the PPE about half or less of the time they worked. Eye protection was worn an average 46.8% of the time, and hearing protection 12.4% of time. Gloves and hard hats were worn 56.0% of the time, while harnesses were worn 31.9% of the time. Finally, with one exception, participants generally reported that they believed that each type of PPE was important. Most reported eye protection (93.4%), hearing protection (55.4%), hard hats (52.6%), and harnesses (86.7%) to be important. Gloves were stated to be important by 36.0% of participants.

Injuries

Four (4.5%) of the roofers reported having fallen while working in the past year; none reported an electrical shock (Table IV). The most common injuries reported by participants were cuts (20.2%), bruises (16.9%), and strains or sprains (14.6%). Other injuries were less frequent, though important: 5.6% reported a burn, 2.3% reported a dislocated joint or head injury, and 1.1% reported a broken bone. Thirty-five (39.3%) workers had experienced Any Injury.

Association of Perceived Work Safety Climate with PPE Use and Injuries

Greater work safety climate was significantly associated with each type of employer-provided PPE, with the exception of a safety harness (Table V). Work safety climate was significantly associated with participants reporting they used each type of PPE most or all of the time. Work safety climate was significantly associated with the percent of time participants used goggles, gloves, and hard hats, but not ear plugs or safety harnesses. Work safety climate was not associated with beliefs about the importance of any PPE.

Work safety climate had a significant inverse association with participants experiencing a cut or laceration in the last 12 months ($p = 0.0147$) (Table VI). The mean work safety climate score for those who did not experience a cut or laceration was 27.2 (SD = 5.5), and it was 23.6 (SD = 5.4) for those who did experience a cut or laceration (Table V). Work safety climate had a borderline association with participants who experienced a bruise or contusion in the last 12 months ($p = 0.0915$). The mean work safety climate score for those who did not experience a bruise or contusion was 26.8 (SD = 5.9), compared to 24.9 (SD = 3.4) for those who did experience a bruise or contusion. Finally, work safety climate had a borderline association with participants who experienced any injury in the last 12 months ($p = 0.0723$). The mean work safety climate score for those who did not experience any injury was 27.3 (SD = 5.8), compared to 25.1 (SD = 5.0) for those who did experience any injury.

Discussion

Latino workers reported that their employers generally provided six types of PPE (eye protection, hearing protection, cut-resistant gloves, abrasion-resistant gloves, hard hats, and safety harnesses), that they generally used the PPE (with the exception of hearing protection) most or all of the time, and generally that using the PPE (with the exception of gloves) was important. Use of each type of PPE was lower when measured by the percent of the time used with the daily logs than was reported retrospectively in the baseline interview. The levels of employers providing each type of PPE are similar to those previously reported for Latino

construction workers that included framers and general construction workers, as well as roofers (Grzywacz et al., 2012b). However, based on daily logs, participants in this study used the PPE half or less of the time they worked. Injuries were commonly experienced, with two in five reporting some injury in the previous 12 months.

Work safety climate (mean = 26.5, SD = 5.6) was higher for these participants than that reported for a different study of Latino construction workers. Work safety climate for this other group of North Carolina Latino construction workers was 23.0 (SD = 5.3) for the entire sample, 24.3 (SD = 4.8) for framers and for general workers, and 19.9 (SD = 5.6) for roofers (Arcury et al., 2012b). It was similar to levels reported for Latino manufacturing workers in North Carolina, for whom it was 24.8 (SD = 3.2) based on 9 of the 10 scale items (Arcury et al., 2012c, 2013), and Latino farmworkers in North Carolina, for whom it was 26.6 (SD = 4.0) (Arcury et al., 2012a). It was greater than levels reported for Latino horse farm workers (20.8, SD = 5.5) and crop workers (20.9, SD = 6.2) in Kentucky (Swanberg et al., 2013). Several of the specific items in the work safety climate scale indicate dissidence in safety perceptions among the participants. Although, few participants felt that taking risks was not part of their job and that their supervisors do as much as possible to make the job safe, most felt that safety practices were very important to management and that they were made of aware of dangerous practices and conditions. This dissidence is also common in the studies of other Latino workers (Quandt et al., 2008; Kiefer et al., 2009; Arcury et al., 2014).

Consistent with other research (Neal & Griffin, 2002; Zohar, 2010), better work safety climate is associated with fewer injuries. The associations of work safety climate with safety behaviors as indicated by the use of PPE, and safety beliefs, as indicated by how important workers felt each type of PPE to be, presents an interesting picture. Latino residential roofers' perceived work safety climate is generally associated with reported behavior related to employers providing PPE and workers using PPE. If work safety climate is a measure of how workers perceive their supervisors value safety over productivity, then the associations between work safety climate and PPE use reflect what is generally reported for Latino workers. That is, their behavior reflects what they perceive their supervisors value (Arcury et al., 2012a, 2013; Keifer et al., 2009; Grzywacz et al., 2007; Quandt et al., 2006). For example, in previous research (Grzywacz et al., 2012b), use of PPE increased if it was provided at no cost to construction workers by their employers. Work safety climate was not related to how important workers felt each type of PPE to be. If workers' use of PPE is based on whether they perceive it to be important to their supervisors, then whether they value PPE use is not relevant to their behavior.

PPE is at the bottom of the hierarchy of control for occupational safety. The use of PPE usually represents the failure of the safety system, and its disuse in many circumstances would reflect greater perceived work safety climate. However, current programs to reduce construction injuries and falls (e.g., Williams et al. 2010; Ochsner et al., 2012; Menzel & Shrestha, 2012; Forst et al., 2013) include increased PPE use and behavior change. This places the onus of safety on the worker rather than the employer. Workers generally dislike the use of PPE. It seldom fits well, is uncomfortable, and restricts movement; this dislike of PPE use is true for Latino roofers (Arcury et al., 2014). The use of PPE by participants in this study, when it is supported by their supervisors, indicates that this use reflects positive perceived work safety climate.

This analysis can only report on the percent of time that participants used PPE. It cannot determine the percent of time that PPE should have been worn to reduce an exposure to a hazard. For example, if a worker works at heights for only 6 hours out of an 8 hour day, then

fall protection is only needed for 75% of the day. This is a limitation of this analysis. However, several types of PPE, including eye protection, gloves, and hardhats, should always be worn on a worksite as some hazards are omnipresent. Similarly, this analysis cannot report if a participant received training in the use of a specific type of PPE, and if this training was related to its use. For example, if a worker is not trained in the proper use of a safety harness, the use of this PPE may not provide any protection. This is also a limitation. However, several types of PPE, including eye protection, hearing protection, gloves, and hardhats, require little or no training for their proper use.

The results of this research should be evaluated in light of their limitations. This research was based on a non-random sample from a single state; both of these factors indicate that generalizations should be made with caution. The relative high levels of PPE use among the participants and their relatively high level of perceived work safety climate may indicate that these participants are not representative of Latino roofers; however, other research has found that foreign-born Latino workers have more positive safety attitudes than do US-born workers (Sokas et al., 2009). The research uses cross-sectional data which indicate association rather than causation.

The results indicate that work safety climate reflects safety behaviors in the use of PPE, but not beliefs about the importance of PPE. Whether Latino workers believe PPE is important, their behavior improves when they perceive safety to be important to their supervisors; however, only one in five participants stated that they believed that their supervisors do as much as possible to make their jobs safe. Greater work safety climate is also indicative of fewer injuries. Therefore, supervisors supporting and modeling safe behavior may improve use of PPE, even if the individual roofers do not believe the PPE is important to safety. For example, Kines and colleagues (2010) argue that coaching construction supervisors to include safety in their daily verbal exchanges with workers has a positive and lasting effect on the safety and reduction of work-related injuries. Regular safety meetings would provide the opportunities for supervisors to praise safe conduct and reinforce the importance of proper PPE use for safety and injury prevention. Supervisors using proper PPE would further reinforce these behaviors.

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Table I. Personal and General Work Characteristics, Latino Residential Roofers, 2012-13 (n = 89).

Personal and General Work Characteristics	Mean	SD
Age	34.6	7.9
Years lived in the US	12.6	3.6
Years lived in NC	9.9	4.8
Years of education	8.2	3.0
Years working as a roofer	7.4	4.8
Weeks in the last year working as a roofer	38.6	14.0
Hours per week in the last year working as roofer	39.1	8.5
	n	%
Country of origin		
Mexico	76	85.3
Other	13	15.6
Language spoken as a child		
Spanish	85	95.5
Indigenous	4	4.5
Pay schedule		
Hour	76	85.3
Day	7	7.9
Week	2	2.2
Roof	4	4.5
Number of contractors worked for in past year		
One	69	82.1
More than one	15	17.9
Ever received formal roofing training	52	58.4
Ever received safety training in roofing	54	60.7
Ever received training on ladder safety	61	68.5

Table II. Work Safety Climate, Latino Residential Roofers, 2012-13 (n = 89).

Work Safety Climate Items	Agree/Strongly Agree	
	n	%
Workers' safety practices are very important to management	77	86.5
Workers have almost total control over personal safety	77	86.5
Workers are regularly made aware of dangerous work practices or conditions	71	79.7
Proper safety equipment is always available	67	75.3
Workers attend regular safety meetings	50	56.2
Workers are regularly praised for safe conduct	48	53.9
Workers receive instructions on safety when hired	47	52.8
Taking risks is not a part of my job	26	29.2
The possibility of being injured at work in the next 12 months is very likely*	74	83.1
Supervisors do as much as possible to make my job safe	18	20.5

*Reverse scored

Table III. Reported, and Actual Use of PPE, Latino Residential Roofers, 2012-13.

PPE	Baseline (n = 89)				Daily Logs (n = 78 logs, n = 72 worked)				
	Provided by Employer		Reported Use Most/All of the Time		% Time Used	Beliefs			
						Not Important		Important	
	n	%	n	%		n	%	n	%
Eye protection	58	65.9	61	68.5	46.8	5	6.6	71	93.4
Hearing protection	35	40.2	25	28.1	12.4	34	44.7	42	55.3
Cut-resistant gloves	51	59.3	56	62.9					
Abrasion-resistant gloves	47	54.7	58	65.2	56.0	48	64.0	27	36.0
Hard hat	70	81.4	63	71.6	56.3	36	47.4	40	52.6
Safety harness	80	93.0	51	57.3	31.9	10	13.3	65	86.7

Table IV. Falls and Occupational Injuries Experienced in Last 12 Months, Latino Residential Roofers, 2012-13 (n = 89).

	n	%
Fall while working in roofing	4	4.5
Injuries		
Cut or laceration	18	20.2
Bruise or contusion	15	16.9
Strain or sprain	13	14.6
Flame or chemical burn	5	5.6
Head injury (e.g., concussion or knocked unconscious)	2	2.3
Dislocated joint	2	2.3
Broken or fractured bone	1	1.1
Electrical shock	0	0
Any other injury	3	3.4
Any Injury	35	39.3

Table V. Associations of Work Safety Climate Score with PPE Provided, PPE Used Most or All of the Time, and Percent of Time PPE Used, Latino Residential Roofers, 2012-13 (n = 89).

PPE	Spearman Correlation with Work Safety Climate Score	p-value
PPE Employer Provided (baseline)		
Eye protection	.23	.0297
Hearing protection	.40	.0001
Cut-resistant gloves	.36	.0008
Abrasion-resistant gloves	.44	<.0001
Hard hat	.25	.0188
Safety harness	.13	.2395
PPE Used Most or All of the Time (baseline)		
Eye protection	.25	.0173
Hearing protection	.34	.0011
Cut-resistant gloves	.28	.0085
Abrasion-resistant gloves	.26	.0135
Hard hat	.24	.0238
Safety harness	.25	.0201
Percent of Time PPE Used (daily logs)		
Eye protection	.28	.0288
Hearing protection	-.06	.6580
Gloves	.27	.0411
Hard hat	.31	.0162
Safety harness	.01	.9200
Beliefs about Importance (daily logs)		
Eye protection	.04	.7378
Hearing protection	-.10	.3989
Gloves	.15	.1943
Hard hat	-.03	.8067
Safety harness	-.03	.8002

Table VI: Association of Work Safety Climate Score with Injuries Experienced in Last 12 Months, Latino Residential Roofers, 2012-13.

Injuries	Work Safety Climate Score Mean (SD)		p-value
	Not Injured	Injured	
Strain or sprain	26.5 (5.9) (n=76)	26.3 (3.7) (n=13)	.8766
Cut or laceration	27.2 (5.5) (n=71)	23.6 (5.4) (n=18)	.0147
Bruise or contusion	26.8 (5.9) (n=74)	24.9 (3.4) (n=15)	.0915
Any injury (sprain, cut, bruise, burn, broken bone, dislocated joint, head injury, shock, or other injury)	27.3 (5.8) (n=53)	25.1 (5.0) (n=35)	.0723

3. Intervention Evaluation

Abstract

Background: This analysis describes results of an intervention to improve safety knowledge and worksite safety practices concerning falls and other hazards among Latino roofers.

Methods: North Carolina residential roofers were randomized to either a fall safety intervention or a control condition, which provided wage theft information. 37 intervention and 30 control participants completed a baseline and at least one of two follow-up data collections, consisting of a 7-day diary using a computer-assisted telephone survey (CATS) designed to capture safety practices relevant to falls on the job on one day; it asked about specific behaviors performed while on the job site that day. Outcome measures included safety knowledge, safety behaviors, and PPE usage.

Results: No significant differences were found between intervention and control participants in any of the outcome measures. Large amounts of missing data were present in the CATS data.

Conclusions: This study was inconclusive. The apparent participant burden of using the CATS system was large. It is also likely that the intervention was too weak to produce measureable change in knowledge or behavior.

Introduction

Construction is among the riskiest occupational sectors, and the burden of poor occupational health in construction is disproportionately borne by immigrant Latino workers. Illness and injury rates among construction workers are likely underestimated, especially among immigrant workers, who view hazards as part of the job, are intimidated from reporting injuries, or they move on to other jobs as symptoms develop, especially if they limit work activity.

Special issues in safety for Latino construction workers include: language barriers, cultural barriers, lack of understanding of rights to a safe work environment, fear of deportation. Many of the existing construction safety interventions have focused on Latino construction workers in commercial, not residential, construction and those workers in unions. However, a large number of Latinos work in residential construction, either as employees of residential construction firms (small and large) or as independent contractors. Because of these employment situations, these workers are much less likely to work on jobsites where employers are aware of safety requirements, where regular safety training takes place, or where occupational safety and health inspections occur.

In this report we focus on Latino residential construction workers, specifically roofers, in North Carolina. Based on previous qualitative and quantitative research with roofers and experience implementing interventions with Latino workers in the community using a lay health advisor approach, we develop, implement, and evaluate a community-sited intervention focused on knowledge and work practices to prevent falls and other occupational injuries common to roofers. The goals of paper are: (1) to describe a community-delivered intervention to improve construction worker safety knowledge and worksite safety practices, and (2) to evaluate the

intervention's effectiveness in a single-blind, controlled trial to improve safety knowledge and practices.

Methods

Study Design and Recruitment

A community-based participatory research framework was used to implement this intervention intended to determine the efficacy of a lay health advisor (LHA) based falls prevention program. HOLA of Wilkes county and El Buen Pastor were the Community organizations in charge of implementing the LHA program, while the research team at Wake Forest School of Medicine and consultants from Virginia Tech Center for Innovation in Construction Safety and Health Research collaborated in the development and the evaluation of the educational material. All study procedures were approved by Wake Forest School of Medicine Institutional Review Board.

The intervention was implemented in Forsyth and Wilkes Counties in North Carolina and it took place over a 17-month period from August 2012 to February 2014. Participants were recruited by LHAs from a list of community sites and locations frequented by immigrant Latino construction workers such as construction sites, tiendas, laundromats, and churches. LHAs were native Spanish speakers and were members of the community. To participate in the intervention, the participant had to 1) be 18 years or older, 2) self-identify as Latino or Hispanic, 3) be employed 30 or more hours per week as a roofer in the residential construction industry, and 4) expect continuous employment for the 3 months after recruitment. A total of 89 participants were recruited at baseline, and 67 completed the baseline questionnaire and pre-test (T_0), and the first post-test (T_1). The sample for analysis was restricted to those 67 workers. This restriction set the maximum sample size for any analysis at 37 for the fall prevention intervention and 30 for the wage theft control

Study Intervention

After participants were recruited and agreed to participate, they were given a baseline questionnaire that lasted about thirty minutes. The baseline questionnaire assessed demographics, occupational characteristics, and health outcomes. Participants were given \$15 as compensation for completing the interview. After the completion of the baseline questionnaire, participants were asked to complete a 7-day diary using a computer-assisted telephone survey (CATS) that took approximately 15 minutes to complete; participants were given \$20 for completing that phase of the intervention. CATS was designed to capture safety practices relevant to falls on the job on one day; it asked about specific behaviors performed while on the job site that day.

To test the efficacy of the fall prevention program once the participants completed the baseline and the CATS, they were randomly assigned to either a fall prevention (Intervention) or a wage theft (Control) lesson. The Wage Theft lesson was assigned to the control group. The teaching method used in both LHA-based lessons was based on the principles of active learning. The LHAs were trained in Spanish to impart verbal lessons where learners were invited to discuss the information. The fall prevention lessons were developed in English and

Spanish from in-depth interviews conducted among roofers about their work safety perceptions; including risks of injury, usage of personal protective equipment, work safety, and safety training (Arcury et al., 2013). The lesson was designed to change knowledge and behavior in four areas: 1) *see safety* - to have workers inspect the work area for any visible safety hazards and to fix and mark them; 2) *climb safety* – to ensure the ladder is properly secured prior to climbing it, and to make sure workers are properly climbing it; 3) *fall safety* - to encourage the use of barriers to prevent falls, and the proper placement of walkboards; and 4) *wear safety* – to encourage the proper use of PPE. The lessons used for the control group were lessons on wage theft developed and used by Wake Forest School of Medicine researchers in conjunction with community organizations. The lesson's main purpose is to educate workers about their rights and what to do when they are not properly remunerated for their work.

Study Evaluation and Data Analysis

To evaluate the efficacy of the fall prevention program, CATS was used to conduct a test pre and post intervention. The test consisted of 78 questions that assessed safety beliefs and attitudes (e.g., Can you usually tell by looking at the roof whether it is more or less dangerous?), job exposures (e.g., Were there slide guards on the roof you worked today?), safety climate (e.g., Did you have all the safety equipment you needed today?), use of PPE (e.g., How many hours today did you wear a hardhat?), safety behavior (e.g., Did you or another safety worker put up a safety barrier on the roof you worked today?), occupational health (e.g., Were you hurt or injured in any way at work today?), and behavioral intentions and change (e.g., In the next 30 days do you think you will start wearing gloves more than you usually do? In the past 30 days did you start using any type of PPE more regularly? After analyzing the call logs and frequencies, the research team concluded that the intervention could be defined as completed if the participant had a baseline questionnaire done, called at least 3 days after the baseline questionnaire and prior to receiving the lesson, received the lesson, and completed at least one call after receiving the lesson.

To assess whether the intervention was successful 13 questions were used to assess safety knowledge, 8 questions were used to assess safety behavior, and 5 questions were used to assess PPE usage. Where necessary, items were reverse scored so that results could be presented as “correct” or “incorrect. In analyses, don’t know and refused” were considered incorrect. In order to classify PPE usage as correct or incorrect, hours of reported PPE usage were divided by the number of hours a worker reported working on the roof. Distributions of the resulting variables were examined. For two types of PPE where usage was very low (ear plugs and harnesses), the variables were dichotomized such that any usage was considered correct. For the other three types, a median split was used to dichotomize correct/incorrect usage.

Results

Table 1 compares the intervention and control group performance on 13 safety knowledge items as well as a total score. There are no significant differences for individual items or mean total score at any time point. Some items (e.g., importance of safety glasses and need to wear harness) had a very high percentage correct at baseline, so there was little room for improvement. Other items (e.g., PPE affecting work speed) did have room for improvement, but none occurred.

Table 2 compares the mean total scores for safety knowledge between time points. In the intervention group, mean changes are positive; in the control group two changes are negative suggesting a decline in knowledge. However, standard deviations are extremely large (over three times the mean in all cases) and not statistically significant.

Table 3 compares the intervention and control group performance for 8 safety behaviors calculated from the daily diaries. There were no statistically significant differences between intervention and control at any time point. For two items involving walkboards over half the individuals had too little data to be included, suggesting that walkboards were not in use.

Table 4 compares the intervention and control group performance for wearing PPE, as obtained from the daily diaries. There was considerable missing data at each of the three time points. At baseline, the control group reported significantly greater use of harnesses. This trend continued, but was not significant, at the follow-ups. The intervention group had significantly more hardhat wear at the second follow up. There were no other significant differences.

Discussion

The intervention had no effect. Several factors may account for this lack of an effect. A small number of participants enrolled in the study, and a high percentage of these participants did not complete the intervention or evaluation, limiting statistical power to detect differences. Reasons for not enrolling and drop-out included perceived burden and unwillingness to jeopardize employment.

The context of the intervention required a large dose. Workers were afraid to participate in the safety training or evaluation because they did not want to alienate their employers (this also limited overall participation). Workers needed the income from their jobs and did not want to make changes that would alienate their employers. Workers (qualitative analysis) indicated that they valued production and income over safety; they did not want to alienate their co-workers by slowing the crew for safety. Workers (baseline analysis) indicated that they used PPE when they perceived it to be important to their employers, even when they did not believe it made them safer.

Efforts should address increasing the work safety climate and employer support of safety and PPE use. This will provide the context for providing safety training for workers.

Table 1. Comparison of safety knowledge items and total score, by Intervention and Control, at T₀, T₁, and T₂.

	Baseline (T ₀)			Week 5 (T ₁)			Week 10 (T ₁)		
	Intervention N=37	Control N=30	P- value	Intervention N=37	Control N=30	p- value	Intervention N=28	Control N=23	p- value
	Correct N (%)	Correct N (%)		Correct N (%)	Correct N (%)		Correct N (%)	Correct N (%)	
Can tell if roof is dangerous	4 (10.8)	3 (10.0)	.91	4 (10.8)	4 (13.3)	.75	3 (10.7)	3 (13.0)	.80
Know if task requires extra caution	1 (2.7)	1 (3.3)	.88	2 (5.4)	2 (6.7)	.83	2 (7.1)	0 (0)	.19
Good at deciding whether working conditions can lead to an injury	2 (5.4)	2 (6.7)	.83	4 (10.8)	1 (3.3)	.25	0 (0)	1 (4.3)	.26
Hard hats are not needed for Roofers	18 (48.6)	16 (53.3)	.70	17 (45.9)	16 (53.3)	.55	17 (60.7)	13 (56.5)	.76
Important to wear safety glasses when working	34 (91.9)	30 (100)	.11	36 (97.3)	27 (90.0)	.21	28 (100)	21 (91.3)	.11
No need for ear plugs or hearing protection	18 (48.6)	18 (60.0)	.35	16 (43.2)	18 (60.0)	.17	15 (53.6)	17 (73.9)	.13
Tennis shoes are best footwear for Roofers	23 (62.2)	16 (53.3)	.57	25 (67.6)	16 (53.3)	.23	18 (64.3)	11 (47.8)	.24
No need to wear work gloves or other hand protection	10 (27.0)	14 (46.7)	.07	17 (45.9)	13 (43.3)	.83	15 (53.6)	10 (43.5)	.47
Should wear harness that is tethered to an anchor regardless of the type of roof working on	33 (89.2)	26 (86.7)	.95	30 (81.1)	27 (90.0)	.43	26 (92.8)	18 (78.3)	.13
Workers that use PPE work slower	6 (16.2)	7 (23.3)	.38	12 (32.4)	9 (30.0)	.77	10 (35.7)	7 (30.4)	.69
Tying off ladders is a hassle and waste of time	27 (73.0)	23 (76.7)	.38	27 (73.0)	23 (76.7)	.88	23 (82.1)	18 (78.3)	.73
Putting up simple barricades on the edge of the roof sounds good but they don't do anything	21 (56.8)	18 (60.0)	.54	19 (51.4)	21 (70.0)	.15	18 (64.3)	11 (47.8)	.24
Once on job site the sooner everyone gets to work the better off everyone is	20 (54.0)	11 (36.7)	.24	21 (56.8)	16 (53.3)	.68	15 (53.6)	11 (47.8)	.68

Score Mean (SD)	5.9 (2.4)	6.2 (2.2)	.60	6.2 (2.4)	6.4 (1.9)	.69	6.8 (2.1)	6.1 (1.9)	.25

NOTE #1: number of respondents varies slightly from cell to cell. For Phase I, Intervention N is constant at n=37, whereas the Control N ranges from N= 28 to 30. Percentages were based on the N specified in the column heading (i.e., n=37 or n=30), while p-values were based on the actual N with data. For Phase II, total N only varied by 1 N ranged from 66 to 67). For Phase III, N was constant at 51.

NOTE #2: response codes “don’t know” and “refused” were coded as “Incorrect”.

Table 2. Differences in Safety Knowledge Scores

	Intervention Mean(SD)	p- value	Control	p- value	Between-test p-value
Phase II – I	0.4 (1.8) n=37	0.25	0.3 (1.9) n=30	0.45	0.85
Phase III – I	0.5 (1.7) n=28	0.13	-0.1 (1.6) n=23	0.79	0.21
Phase II – I	0.5 (1.7) n=28	0.10	-0.2 (1.9) n=23	0.66	0.16

NOTE: differences do not match those that one can calculate from means provided in Table I due to different N’s—the N’s in this table require that the participant have data at both time points being compared, whereas in Table I, the means are based on whoever has values at a single time point.

Table 3. Comparison of safety behavior items, by Intervention and Control, at T₀, T₁, and T₂

	Baseline (T ₀)			Week 5 (T ₁)			Week 10 (T ₁)		
	Interventi on N= 36	Control N= 26	p- valu e	Interventi on N= 34	Control N= 28	p- valu e	Interventi on N= 25	Control N= 23	p- valu e
	Percent of Days Behavior Performed N=36	Percent of Days Behavior Perform ed N=26		Percent of Days Behavior Performe d N=34	Percent of Days Behavior Perform ed N=28		Percent of Days Behavior Performe d N=25	Percent of Days Behavior Perform ed N=23	
Make sure that all roof openings were covered	93%	98%	.08	97%	87%	.06	88%	92%	.44
Marked off safety zones on the roof you worked today	66%	63%	.57	64%	59%	.56	70%	60%	.31
Worker put up a safety barrier on the roof you worked today	58%	63%	.21	55%	55% (n=27)	.34	63%	47%	.27
Look for hazards on the job site	84%	75%	.46	91%	73% (n=27)	.06	95%	72%	.09
Make sure the top of it of the ladder tied off to the structure	93% (n=34)	94% (n=25)	.75	100% (n=33)	95% (n=26)	.17	100%	89%	.07
Carry any shingle bundles or other materials in your hands while on the ladder	17% (n=34)	30% (n=25)	.13	14% (n=33)	26% (n=26)	.18	17%	40%	.16
Verify that all the walkboard brackets were nailed to a rafter***	95% (n=15)	100% (n=11)		100% (n=10)	100% (n=10)		100% (n=6)	100% (n=8)	
Any of the walkboards you worked on have overlapping boards***	78% (n=15)	63% (n=11)		72% (n=10)	58% (n=10)		54% (n=6)	61% (n=8)	

NOTE: values in table are average percent of days workers performed the safety behavior. P-value was obtained using a weighted chi-square test, where participants who worked more days had a higher impact on results than those who worked fewer days

*** These variables have a large volume of missing data. This is apparently due to the infrequent use of walkboards.

	Baseline (T ₀)			Week 5 (T ₁)			Week 10 (T ₁)		
	Intervention	Control	P- value	Interventio	Control	p- value	Intervention	Control	p- value
	N= 32	N= 24		n N= 28	N= 27		N=21	N= 21	
	Correct n/N(%)	Correct n/N(%)		Correct n/N(%)	Correct n/N(%)		Correct n/N(%)	Correct n/N(%)	
Goggles	15/32 (46.9%)	13/24 (54.2%)	0.20	13/28 (46.4%)	15/25 (60.0%)	0.56	11/19 (57.9%)	10/21 (47.6%)	0.10
Ear plugs	8/27 (29.6%)	10/23 (43.5%)	0.07	8/23 (34.8%)	7/24 (29.2%)	0.51	5/20 (25.0%)	7/21 (33.3%)	0.86
Hardhats	16/29 (55.2%)	11/24 (45.8%)	0.16	11/28 (39.3%)	12/27 (44.4%)	0.91	10/20 (50.0%)	8/21 (38.1%)	0.05
Harness	15/28 (53.6%)	18/24 (75.0%)	0.02	14/25 (56.0%)	16/25 (64.0%)	0.67	10/21 (47.6%)	12/20 (60.0%)	0.11
Gloves	16/29 (55.2%)	11/24 (45.8%)	0.14	14/26 (53.8%)	13/27 (48.2%)	0.48	13/20 (65.0%)	10/21 (47.6%)	0.06

NOTE: n/N is provided in each cell to show where missing data occurs

NOTE: P-values obtained from a weighted chi-square test, where participants who worked more days had a higher impact on results than those who worked fewer days

4. Enrollment Table

This report format should NOT be used for data collection from study participants.

Study Title: Prevenir Cadas: An LHA-Based Approach to Safety Education Among Latino Roofers
Total Enrollment: 99 **Protocol Number:** IRB00017835
Grant Number: U60 OH009761-05 Project 10183

PART A. TOTAL ENROLLMENT REPORT: Number of Subjects Enrolled to Date (Cumulative) by Ethnicity and Race				
Ethnic Category	Females	Males	Sex/Gender Unknown or Not	Total
Hispanic or Latino		99		99 **
Not Hispanic or Latino				
Unknown (individuals not reporting ethnicity)				
Ethnic Category: Total of All Subjects*		99		99 *
Racial Categories				
American Indian/Alaska Native				
Asian				
Native Hawaiian or Other Pacific Islander				
Black or African American				
White		5		5
More Than One Race		94		94
Unknown or Not Reported				
Racial Categories: Total of All Subjects*		99		99 *
PART B. HISPANIC ENROLLMENT REPORT: Number of Hispanics or Latinos Enrolled to Date (Cumulative)				
Racial Categories	Females	Males	Sex/Gender Unknown or Not	Total
American Indian or Alaska Native				
Asian				
Native Hawaiian or Other Pacific Islander				
Black or African American				
White		5		5
More Than One Race		94		94
Unknown or Not Reported				
Racial Categories: Total of Hispanics or		99		99 **

5. Publications

Arcury TA, Summers P, Carrillo L, Grzywacz JG, Quandt SA, Mills T: [2014] Occupational Safety beliefs among Latino residential roofing workers. *American Journal of Industrial Medicine* 57:718-725.

Arcury TA, Summers P, Rushing J, Grzywacz JG, Mora D, Quandt SA, Lang W, Mills T: [2015] Work safety climate, personal protection use, and injuries among Latino residential roofers. *American Journal of Industrial Medicine* 58(1):69-76.

Lane CM, Jr., Grzywacz JG, Marín AJ, Carrillo Holbrook L, Mills T, Quandt SA, Arcury TA: [2012] *Get Smart Working in Roofing! / ¡Ponte Listo Trabajando en Roofing!* Winston-Salem, NC: Wake Forest School of Medicine.

6. Material available for other Investigators

Lay health advisor lesson plan
Get Smart Working in Roofing!
¡Ponte Listo trabajando en roofing!

Flipchart: Lane CM, Jr., Grzywacz JG, Marín AJ, Carrillo Holbrook L, Mills T, Quandt SA, Arcury TA. *Get Smart Working in Roofing! / ¡Ponte Listo Trabajando en Roofing!* Winston-Salem, NC: Wake Forest School of Medicine, 2012.

Software: Computer-Assisted Telephone Surveys (CATS) software

To obtain materials contact:

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Project ID 10302 – Prevention through Design (PtD) Adoption Readiness
Final Progress Report

Prevention through Design (PtD) Adoption Readiness:
Control of Health Hazards in Concrete, Masonry, and Asphalt Roofing

Grant Number: U60 OH009761-03 Project ID 10302

August 2012 – August 2014

Project PI: Deborah Dickerson (Young-Corbett)

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Report Date: 4/26/15

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Abbreviations

AIHA	American Industrial Hygiene Association
ASSE	American Society of Safety Engineers
AWCI	American Wall and Ceiling Institute
CFA	Confirmatory factor analysis
DOI	Diffusion of Innovation Model
DUSTI	Dust-control Usage: Strategic Technology Intervention
FCA	Finishing Contractors Association
GFI	Goodness of fit index
HBM	Health Belief Model
IARC	International Agency for Research on Cancer
LEV	Local-exhaust ventilation
MSDS	Material safety data sheets
NSC	National Safety Council
OEL	Occupational exposure limit
OHS	Occupational health and safety
OSHA	Occupational Safety and Health Administration
PtD	Prevention through Design
PtDARM	Prevention through Design Adoption Readiness Model
PEOU	Perceived ease of use
PU	Perceived usefulness
R&D	Research and Development
SES	Self Efficacy Scale
SIC	Standard Industrial Classification
SME	Subject Matter Expert
TAM	Technology Acceptance Model
TRI	Technology Readiness Index

Abstract

Project Title: Prevention through Design (PtD) Adoption Readiness: Control of Health Hazards in Construction

Principal Investigator: Deborah Dickerson (Young-Corbett), PhD

Contact Information: debdickerson@vt.edu

Concrete operations, asphalt roofing, and welding are associated with some of the most pressing occupational health hazard risks in construction. Prevention through Design (PtD) solutions, the preferred method of reducing risk to workers, do exist to control the hazards associated with these construction operations. The extent to which they are currently employed in actual construction practice has yet to be documented. A baseline understanding of current usage trends is needed, in order to establish targets for PtD control adoption. Further, understanding the barriers that prevent the adoption of PtD technologies is needed so that future intervention strategies can advance diffusion within the construction industry. Therefore, the funded work documented the current usage trends, constructs associated with adoption readiness, and barriers associated with PtD control technologies in the concrete, masonry, asphalt roofing, and welding trades.

A telephone survey of decision-makers in the concrete ($n = 167$), masonry ($n = 230$), and asphalt roofing ($n = 199$) trades was conducted to quantify current usage rates of key PtD tools. Familiarity with the tools, usage rates of the tools, and perceptions of the tool benefits were measured with a 5-point Likert-type scale. Barriers to tool usage were elicited via open-ended questions. The following dust-control innovations were evaluated for concrete and masonry trades: ventilated tools, wet-methods, sweeping compounds, and isolation systems. For asphalt roofing, the innovations evaluated were: tanker delivery systems, ventilated kettles and hot-lugger systems, mechanized asphalt spreaders, and low-fume asphalt material.

Section 1: Final Progress Report

Key Findings

Results. Based on the percentage of participants reporting their firm usage rate as either “always” or “regularly”, the most commonly used methods of dust control in the concrete and masonry trades were wet methods (81.2%), ventilated tools (58.2%), sweeping compound (30.3%), and isolation systems (12.6%). Respondents reported a high perception of risk to worker health from the concrete and masonry dust (73.6% ‘strongly agree’ or ‘somewhat agree’). Governmental regulations and insurance incentives were listed as the most pressing drivers for deciding to use dust control technology. Disruption to productivity and job performance were listed as the main barriers to dust-control use in these trades.

Based on the percentage of participants reporting their firm usage rate as either “always” or “regularly”, the rates of usage of methods of asphalt fume control in roofing are ventilated/insulated kettles (28.1%), mechanized asphalt spreaders (26.5%), low-fume asphalt material (20.5%) and tanker delivery systems (6.5%). Respondents did not have a very high perception of the risk to worker health associated with asphalt fume (12.5% strongly agree). The biggest motivator to adopt fume control technologies was worker safety (76%). The biggest barrier to adoption was cost (83%).

Translation of Findings

The findings of this work can be directly applied to improve construction safety and health. To improve worker and contractor willingness to use safety equipment, training interventions can be developed based on the findings of these studies, in the following ways. Training should emphasize the health risks associated with the work. The findings of this work can also inform future research investigations in several ways. The information about current usage trends, perceptions of risks, barriers, and benefits of dust and fume control technology can be employed in the development of interventions to improve the use of these controls in concrete, masonry, and asphalt roofing trade sectors of the construction industry.

Outcomes/Impact

7. Potential Outcomes

The findings of this work could improve construction safety and health in construction practice in the following ways:

- Development of worker training guidelines
- Improved worker training
- Improved adoption of PtD innovations among workers and contractors

8. Intermediate Outcomes

The findings of this work have the potential to improve construction safety and health management:

- Safety management programs should incorporate the findings of this work
- The trade associations for concrete, masonry, and asphalt roofing have agreed to publish these findings in their trade publications
- The trade journal, Professional Safety, has accepted an article for publication, thus disseminating this work to safety professionals
- Future research is currently underway to develop similar interventions for concrete, masonry, welding, and asphalt roofing trade sectors

9. End Outcomes

The PtDAR project has begun to see some notable impacts:

- The Occupational Safety and Health Administration (OSHA) cited this work in its recent advisory document regarding the control of silica in construction operations.
- Environment Canada has cited this work in a draft regulation regarding quartz exposures.
- The PI was invited to speak at Purdue University's annual event, "The Engineer of 2020" on PtD in engineering design.
- Publications are in review by the Journal of Construction Engineering and Management of the American Society of Civil Engineers.

Section 2: Scientific Report

Background

Concrete operations, asphalt roofing, and welding are associated with some of the most pressing occupational health hazard risks in construction. Prevention through Design (PtD) solutions, the preferred method of reducing risk to workers, do exist to control the hazards associated with these construction operations. The extent to which they are currently employed in actual construction practice has yet to be documented. A baseline understanding of current usage trends is needed, in order to establish targets for PtD control adoption. Further, understanding the barriers that prevent the adoption of PtD technologies is needed so that future intervention strategies can advance diffusion within the construction industry. Therefore, the funded work documented the current usage trends, constructs associated with adoption readiness, and barriers associated with PtD control technologies in the concrete, masonry, asphalt roofing, and welding trades. This work leverages prior NIOSH-sponsored work which developed a conceptual model to describe and predict stakeholder readiness to adopt PtD innovation, the PtD Adoption Readiness Model (PtD ARM), and validated survey instruments to measure model constructs. The PtD ARM and associated survey instruments were originally developed within the drywall finishing trade sector context and were employed in the development of three intervention strategies to facilitate increased PtD adoption within that sector. The currently described research aimed to extend the scope of the conceptual model and validate its applicability to a broader construction industry context. The long-range goal of the Principal Investigator is to employ the findings of this proposed work to develop construction industry-wide interventions to improve the diffusion of PtD innovation.

Prevention through Design (PtD)

The optimal method of preventing occupational illnesses, injuries, and fatalities is to “design out” the hazards and risks; thereby, eliminating the need to control them during work operations. This approach involves the design of tools, equipment, systems, work processes, and facilities in

order to reduce, or eliminate, hazards associated with work. Prevention through Design (PtD) has been defined by Schulte et al. (2008) as:

The practice of anticipating and “designing out” potential occupational safety and health hazards and risks associated with new processes, structures, equipment, or tools, and organizing work, such that it takes into consideration the construction, maintenance, decommissioning, and disposal/recycling of waste material, and recognizing the business and social benefits of doing so.

The PtD movement saw its genesis in the early 1990’s, with the formation of a committee within the National Safety Council (NSC) to study the feasibility of incorporating safety reduction into design procedures. The outcome of this early work was the formation, in 1995, of The Institute for Safety through Design, with membership from industry, academe, organized labor, and other interested parties (Manuele 2008). Seminars, workshops, and symposia were held throughout the late 1990’s and early 2000’s. In 2006, the Australian government issued a guideline on the Principles for Safe Design for Work, and in 2007 a special edition of Safety Science was published on “Safety by Design”. Also in 2007, the OSHA Construction Alliance Roundtable Design for Construction Safety Group developed a short course entitled, “Design for Construction Safety” and the Institute of Mechanical Engineers held a workshop entitled, “Risk Education for Engineers” (Manuele 2008). One of the goals of the latter was to advance the understanding of the importance of educating undergraduate engineers in risk assessment techniques.

In 2007, the National Institute for Occupational Safety and Health (NIOSH) launched a national PtD initiative; calling on all major industrial sectors to emphasize hazard mitigation at the design stage of tools, facilities, and work processes (Schulte et al 2008). NIOSH partnered with the American Industrial Hygiene Association (AIHA), the American Society of Safety Engineers (ASSE), the Center to Protect Workers’ Rights, Kaiser Permanente, Liberty Mutual, the National Safety Council (NSC), the Occupational Safety and Health Administration (OSHA), ORC Worldwide, and the Regenstrief Center for Healthcare Engineering, in the development of a National Initiative on Prevention through Design, launched in a 2007 workshop and published in a special edition of the Journal of Safety Research in 2008 (Howard 2008). One conclusion of

the 2007 workshop was that there are two major gaps to be addressed in order to advance the implementation of PtD in industry. The first is that design professionals; such as engineers, industrial designers, and architects, need to consider health and safety implications of end-use of their designs. The second is that business decision makers; including, those who purchase products and services, will need to establish a demand for such PtD designs. Therefore, the PtD Initiative aims to focus “both on the supply of innovative design solutions and on creating a demand among business decisions makers who will value and request them” (Schulte et al 2008).

PtD in Construction

In the construction sector, the term “design” is most commonly applied to the process of designing the end-product to be constructed: the building, facility, or infrastructure component. However, PtD has a broader definition and applies to the design of all tools, equipment, materials, and work processes that are employed during the construction process; as well as to the design of the constructed environment itself. Therefore, hazard reduction can be accomplished via a multitude of means; such as, changes in tool selection, material composition, work process management, or facility design. Much of the work done, to date, in PtD in the construction sector has emphasized the reduction of risk in the domain of occupational safety. Occupational safety risks are those that can cause injury or fatality in the event of an accident. This section briefly reviews the body of scholarly work in that domain. One gap in the existing construction PtD literature is in the realm of reduction of occupational health risks. Occupational health risks are those that cause disease or disability in the exposed worker population. Major construction occupational health risks and appropriate PtD strategies will be reviewed in subsequent sections of this paper.

PtD to reduce construction occupational safety risk has received attention in the scholarly literature since the early 1990’s. A pivotal article by Hinze and Wiegand (1992) found that only one third of design firms factored construction worker safety into the design process.

Predominant hazards addressed by those firms factoring safety into design were excavation/trenching and fall risks. Concerns over liability were identified as a major barrier to diffusion in the design community. The Construction Industry Institute conducted a study in the 1990’s to assess and enumerate construction “best practices” for PtD. This study led to the

development of a tool entitled “Design for Construction Safety ToolBox” (Gambatese et al, 1997).

The United States is said to lag behind other developed countries in the diffusion of PtD innovation and adoption of PtD approaches within construction (Toole and Gambatese, 2008). These concepts have been widely accepted throughout the European Union and Australia. Barriers to the diffusion of PtD had been encountered by these countries and lessons can be learned from their experiences. Toole (2005) makes the case that liability concerns may be a larger barrier to PtD adoption in the U.S., due to the litigious nature of the business climate in that country. Toole and Gambatese (2008) identify four key aspects of PtD for emphasis in the near future as the construction industry moves toward embracing a PtD approach. These four focus areas are: increased prefabrication, reduced use of hazardous materials and systems, increased application of construction engineering, and enhanced spatial consideration.

Several large engineering/construction firms attended the 2007 National PtD Initiative Workshop; including Jacobs Engineering, Bechtel, Washington Group, BE&K, Southern Company, Haskell, and Parsons (Behm 2008). Behm (2008) reports that many of these large firms have been proactive in investigating and implementing PtD strategies, but states that industry-wide diffusion of PtD innovation is currently poorly documented and that a clearinghouse of “best practices” is needed. The current article aims to address this gap by providing “best practice” PtD solutions for addressing occupational health risks, with special emphasis on three of the most pressing health hazards presently known to the industry.

Gap in State-of-the-Practice: PtD for Construction Health Hazards

Occupational health risks arise when workers are exposed to chemical, biological, or energetic hazards that might lead to resulting short-term illness, long-term chronic disease, fatal disease, or diminished wellness. Chemical hazards include solvents, finishes, compressed gases, and particulates (e.g.: silica, asbestos, fumes from welding/cutting). Biological hazards include disease-causing microorganisms and allergens. Energetic hazards encompass such agents as noise, vibration, electromagnetic energy and fields, and ionizing radiation. The present section

will review a few of the most notable chemical hazards associated with construction work operations and will present PtD approaches to reducing or eliminating these risks.

The overriding goal of PtD is to eliminate risks where possible, or greatly reduce them when elimination is not possible. For health hazards, the approaches toward reaching this goal fall into three major categories: material substitution, isolation, and process re-design (Table 1). material substitution approaches generally involve selection of less-toxic materials in the place of those with higher toxicity. The construction industry has already experienced several cases of successful material substitution design solutions; such as, the use of man-made mineral fibers in the place of asbestos-containing materials, the use of non-lead paints rather than lead-containing paints, and recent reformulations of finishes to reduce the volatile organic compound components. Isolation solutions are adopted to either isolate the hazardous process or to isolate the workers, as in the case of an enclosed and ventilated equipment cab. Process re-design approaches can be further divided into three categories: wet methods, local exhaust ventilation systems, and work process changes. Wet methods are employed to suppress the generation of particulate health hazards, in various applications (Figure 1). Local exhaust ventilation is a type of ventilation system that removes the hazard at the point of generation, before it has a chance to become entrained in the ambient air and inhaled by workers (ACGIH, 2007). In construction, the most useful local exhaust ventilation is in the form of ventilated tools. Ventilation systems are integrated into construction tools and equipment, to capture contaminants and prevent worker exposure and environmental contamination. Work process changes are adopted to reduce the amount of time a worker is exposed to a hazardous chemical. These changes can involve worker rotation, automation, or prefabrication.

Table 1. Prevention through Design (PtD) Solutions for Chemical Hazards

PtD Solution	Examples for Construction Industry
Category	
Material Substitution	MMMF for Asbestos Limonene for Chlorinated Hydrocarbons

	Latex Paint for Lead Paint
	Alkaline Copper Quaternary (ACQ) for CCA
	Low-dust mud for traditional drywall mud
	Phenol formaldehyde – “low emitting” paint
	Garnet, glass beads, or iron oxide for silica-sand in sandblasting
Process Re-design	
Wet-methods	Vehicle-mounted rock drilling rigs
	Concrete cutting
	Brick cutting
	Pneumatic hand-operated grinders
	Jackhammers
Ventilation	Ventilated drywall sanding tool
	Ventilated concrete sanding tool
	Ventilated masonry saws
Isolation	Asphalt paver enclosed cab
	Ventilated enclosure surrounding masonry saw
	Vehicle-mounted rock drilling rig operator cab
Work Process Re-design	Automation
	Panelization and prefabrication
	Worker rotation

Specific Hazards and PtD Solutions

This section reviews literature concerning some of the highest-risk construction activities for worker exposure to chemical health hazards and presents evidence of effectiveness of corresponding PtD solutions for mitigating those risks. Masonry operations, asphalt roofing, and welding are associated with some of the most pressing occupational health hazard risks in construction. Concrete and masonry operations have been found to generate dust that contains respirable quartz. Quartz (crystalline silica) has well-documented effects on the human respiratory system and has been associated with silicosis, a fibrotic disease of the lung; increased incidence of tuberculosis; and malignant neoplasm of the lung (Knutsson et al, 2000). The International Agency for Research on Cancer (IARC) has classified quartz as a “group I human carcinogen,” a classification indicating that sufficient evidence of causality exists in the scientific literature (IARC, 2003). The construction industry has the highest rate of silica-related occupational fatality among all industrial sectors (Linch et al, 2002). An estimated 800,000 U.S. workers are employed in the Standard Industrial Classification (SIC) code group 174: Masonry, Stonework, Tile Setting, and Plastering. A 1998 examination of OSHA data suggests that this occupational category may have more workers at risk of silica exposure than any other SIC code group (Linch et al, 1998). This study estimated that more than 132,000 masonry workers and more than 118,000 concrete workers are potentially over-exposed to respirable silica, annually.

It has been estimated by the Asphalt Roofing Environmental Council that more than 50,000 United States workers spend an excess of forty percent of their working lives exposed to roofing asphalt (AREC, 1999). Asphalt is the residuum produced by the distillation of crude petroleum. Asphalt fumes and vapors have been associated with both acute and chronic health effects. Studies concerning the acute toxic effects of exposure to asphalt fumes have repeatedly found symptoms of irritation of the mucous membranes of the upper airways, the eyes, and the skin. Mucosal irritation tends to be mild and transient in nature. Skin irritation, pruritus, and occasional rashes have been reported (Norseth et al, 1991). Asphalt-related dermal photosensitization has been suggested, but requires additional investigation to substantiate (Hervin and Emmett, 1976). Studies of roofers have generally demonstrated an excess number of lung cancer cases. A meta-analysis of epidemiologic studies of roofers indicates an excess of lung cancer and neoplasm of the buccal cavity and pharynx among roofers (Partanen and Boffetta, 1994). This 1994 comprehensive review of epidemiologic studies of asphalt workers

found that the relative risk for lung cancer was elevated for asphalt roofers, but not for highway pavers. There have been several cohort mortality studies of roofers exposed to asphalt fumes. A retrospective study of members of the United Slate, Tile, and Composition Roofers, Damp and Waterproof Workers' Association, found that asphalt roofer lung cancer mortality increased with time in job (Engholm et al, 1991). The Swedish Construction Industry's Organization for Working Environment, Safety, and Health conducted a study of cancer mortality and incidence among construction workers, including 704 roofers. Increased mortality for cancer of the lung was observed among roofers. Data from experimental studies in animals and cultured mammalian cells indicate that laboratory-generated roofing asphalt fume condensates are genotoxic and cause skin tumors in mice when applied dermally (McFall et al, 1984). In its Hazard Evaluation report, NIOSH concludes that roofing asphalt fumes are a potential occupational carcinogen, based on the review of epidemiologic studies and the evidence of known carcinogenic constituents in characterization studies (NIOSH, 2001).

More than 400,000 men and women are employed in welding and related occupations in the United States (BLS, 2009). In construction, the predominant welding process is shielded metal arc welding (SMAW). Gas metal arc (GMAW or MIG) and gas tungsten arc (GTAW or TIG) welding are used for special applications. Flux-cored arc welding (FCAW) may also be used but is less common than SMAW. Fumes generated by the manual metal arc or oxy-acetylene welding of iron, mild steel, stainless steel, or aluminum are associated with air contaminants such as particulates, carbon monoxide, vapors, and metal fumes. The welding of iron metals may give off fumes of manganese, silicate, and various organic binders. Aluminum welding may generate fumes consisting of fluorine, arsenic, copper, silicon, and beryllium (Flynn and Susi, 2009). Eighteen different chemical constituents have been measured in the fumes resulting from the welding of mild steel, including fluoride, manganese, silicon, titanium, and sodium or potassium silicates (Flynn and Susi, 2009). Some studies suggest that occupational exposures to welding fumes may pose the risk of serious respiratory, neurological, and reproductive effects. In 2003, NIOSH published a comprehensive review of scientific literature on health effects associated with welding. The article, "Health Effects of Welding," noted that past investigations have found bronchitis, airway irritation, and other respiratory illnesses in large numbers of welders. However, critical differences between the studies and a shortage of dose/response data

make it difficult to compare results and confidently link given exposures with given effects. As the article also noted, some studies have suggested that welding fumes may pose risks for lung cancer and nervous system damage. This is because such fumes may contain nickel, chromium, and manganese. Nickel and hexavalent chromium are classified as potential occupational carcinogens, while studies have associated chronic exposure to manganese with a risk for a Parkinson's-like disease. In a study of the welding industry in Manitoba, Canada, metal fume constituents, carbon monoxide, and ozone were measured during MIG mild steel, MIG stainless steel, and TIG aluminum welding operations. A 2000 task-based exposure assessment of metal fume exposures during welding and thermal cutting found a significant risk to worker health from exposure to manganese, nickel, and chromium VI (Susi et al, 2000).

PtD solutions do exist to control the hazards associated with these construction operations. In the sections that follow, the occupational health hazards associated with these activities, along with their PtD solutions and gaps in the currently available PtD design options, are described in detail.

Concrete and Masonry Hazards

Concrete and masonry operations have been found to generate dust that contains respirable quartz. Many construction materials employed in the construction industry contain quartz: brick, mortar, concrete, slate, dimensional stone (granite sandstone), stone aggregate, tile, asphalt filler, roofing granules, soils, wallboard, joint compound, plaster, putty, and sand used for blasting (OSHA 2009). Quartz (crystalline silica) has well-documented effects on the human respiratory system and has been associated with silicosis, a fibrotic disease of the lung; increased incidence of tuberculosis; and malignant neoplasm of the lung (Knutsson et al, 2000). The International Agency for Research on Cancer (IARC) has classified quartz as a “group I human carcinogen,” a classification indicating that sufficient evidence of causality exists in the scientific literature (IARC, 2003). The construction industry has the highest rate of silica-related occupational fatality among all industrial sectors (Linch et al, 2002). An estimated 800,000 U.S. workers are employed in the Standard Industrial Classification (SIC) code group 174: Masonry, Stonework, Tile Setting, and Plastering. A 1998 examination of OSHA data suggests that this occupational

category may have more workers at risk of silica exposure than any other SIC code group (Linch et al, 1998). This study estimated that more than 132,000 masonry workers and more than 118,000 concrete workers are potentially over-exposed to respirable silica, annually. Tools such as pneumatic hammers and drills, power saws, grinders, chippers, and mills are used frequently in these trades. In a comprehensive industrial hygiene assessment of construction worker chemical exposures, Verma et al. (2003) found that airborne particulate matter was the most prevalent hazard class. In this study of 1,265 task-based assessments, the authors found that dust affects not only the workers involved in direct exposure-causing tasks, but also those performing ancillary activities. Construction tasks evaluated included framing, bricklaying, excavating, foundation building, interior carpentry, insulating, dry walling, painting, and plumbing. Those tasks associated with the highest dust generation were drywall and concrete operations. A study of exposure to silica dust in the U.S. construction industry found that “silica exposures are grossly unacceptable” (Rappaport et al, 2003). Personal sampling was performed for workers in the following trades: bricklayers, abrasive blasters, and laborers. Mixed models were fitted to the log-transformed air levels to estimate the means and variance components of the distributions in each trade. Probabilities of over-exposure were estimated between 64.5 and 100% for silica and between 8.2 and 89.2% for other dust. The authors stated that engineering and administrative controls are needed to reduce worker exposures. The authors concluded that urgent action is needed to address silica over-exposure in the construction industry. The following masonry and concrete operations have been associated with overexposure to respirable silica: surface grinding, saw-cutting concrete, drilling concrete, demolishing, tuck-point grinding, clean-up, concrete mixing, and sack and patch (Flanagan et al, 2003). Studies on the use of handheld masonry saws to cut bricks and concrete blocks found that operators were exposed to silica levels as high as fourteen times the OSHA occupational exposure limit (OEL) of 0.1 mg/m³ (OSHA 2009).

PtD Approaches to Concrete and Masonry Hazard Control

Several PtD control options are available for the reduction of dust generation during concrete and masonry activities. General categories include: local-exhaust tool-mounted ventilation, wet methods, isolation, and sweeping compound for clean-up activities.

Local-exhaust ventilation systems exist for many of the silica-exposing construction operations. Cutting, grinding, and sawing tools can be equipped with local-exhaust ventilation (LEV), which has been found to be very effective (Akbar-Khanzadeh et al, 2001). Ventilated stationary masonry saws are commercially available and have been found to effectively reduce worker exposures to dust (Croteau 2000). Under experimental conditions, a fixed-blade masonry saw ventilation system was found to reduce dust levels by 80 to 95 percent (Croteau et al 2002). Handheld masonry saws can be equipped with vacuum dust collection systems and can be effective at controlling worker exposures. Studies have found these systems to result in reductions of 88 percent (Thorpe et al 1999); however, the exterior hood design employed in the study is yet to become commercially available. A study by Croteau (2002) found that a commercially available system required redesign in order to effectively control the respirable dust from handheld masonry saw operations. Therefore, additional design work is required to improve PtD ventilation systems for handheld masonry saws. Vacuum dust collection systems for hand-operated surface finishing grinders can significantly reduce operator exposures to silica; however, current designs have not been found to reliably keep levels below OSHA limits (OSHA 2009). Re-design efforts to improve ventilation systems for these grinding tools are a suggested area of future research and development, as the ventilation systems have some advantages over wet-methods. Handheld angle grinders used for renovation of deteriorating mortar (tuckpointing/mortar removal) are associated with high operator exposures to respirable silica (Lyons et al 2007; NIOSH 2000). Ventilation systems are readily available for use with these tools; however, they are not widely used in practice (Lyons et al 2007). These systems include a shroud, which surrounds the grinding wheel, and a vacuum to pull air through the shroud. Studies have suggested design flaws in currently available angle grinder ventilation systems, both in terms of usability and effectiveness (OSHA 2009). Additional research is needed to improve industry adoption of this PtD solution for tuck-pointing risks. Rotary hammers and similar tools employed to drill small-diameter holes in concrete and other masonry materials can expose employees to hazardous levels of respirable silica dust (Lofren, 1993). Operations with

these tools are associated with exposures exceeding three times the OSHA OEL. Ventilated tools can significantly reduce risk and are commercially available for handheld drills. These systems enclose the drill bit in a suction ring, which includes a port for attaching a vacuum collection system. These systems have been found to be highly effective, reducing dust by as much as 90 percent (Sheperd et al 2009)(Heitbrink and Watkins 2001).

Wet methods, the wetting of the substrates before or during abrasive operations, have also been found to be effective dust control solutions (Akbar-Khanzadeh et al, 2007). Wet methods are the most effective solution for the control of silica dust during the use of stationary masonry saws. A study of saw operators found exposures to be routinely below 0.1 mg/m³, and usually below 0.05 mg/m³ (NIOSH 1999a). Most stationary saws come equipped with integral wet-method systems. Water-fed handheld saws that are gasoline-powered, air-powered, electric-powered and hydraulic-powered are commercially available. Water can be supplied to the saws either with a pressurized portable water supply or with a constant water source, for example, a municipal water supply. Wet cutting is the most effective method for controlling silica dust during the use of handheld saws (Thorpe et al 1999). Dust levels are reduced by 94 percent for pressurized portable water supply systems and up to 96 percent for constant supplying water sources (Thorpe et al 1999). A reduction of 96 percent resulted in time-weighted average operator exposures of 0.06 mg/m³, a level below the OSHA OEL. Wet methods are available for hand-operated masonry grinders used for surface finishing and cutting slots. Handheld water-fed grinding equipment is commercially available for concrete applications, granite grinding, and polishing operations. Also, conventional grinding equipment can be retrofitted to add a water-feed capability (OSHA 2009). Wet methods consistently keep operator exposures to silica below OSHA limits (Simcox et al 1999). Wet methods are not employed during tuck-pointing operations with an angle grinder, since the addition of water would result in work quality problems. Although not commercially available at the time of this article, an effective means of controlling dust during jackhammer operation, however, is wet-methods. Zalk (2002) found a reduction in silica dust levels from 50 to 98 percent, when workers operated jackhammers with 1/8 gallon per minute water discharge from a retrofitted 90-lb jackhammer. In current practice, manual wetting of surfaces is employed. However, additional research is needed to further

develop water-fed jackhammers, with integral water-supply and distribution mechanisms. Wet methods are generally not appropriate for use with electric rotary hammers, but are available for pneumatic drills. Water-fed pneumatic drills are commercially available, typically marketed for work in explosive atmospheres. These devices have been found to reduce silica exposure risk (CS UNITEC, 2003).

Isolation designs exist for mitigation of some silica-related risks. Enclosure systems for stationary masonry saws have been found to be effective at preventing worker dust exposure, but are not widely available commercially (OSHA 2009). While isolation systems are commonly employed for heavy equipment operations, they remain impractical for most portable hand-operated construction tools.

Sweeping compound is a relatively new PtD solution for the control of worker exposure to dust during clean-up activities on a construction site. Sweeping compound is composed of dyed sawdust, sand, and mineral oil and is broadcast over the floor before sweeping. The added surfactant molecules have a high affinity for most other materials and tend to agglomerate with the dust particles, leading to higher weight-to-surface area ratios and lower tendencies to stay airborne (Westbrooke 1999).

Overview of Asphalt Roofing

It has been estimated by the Asphalt Roofing Environmental Council that more than 50,000 United States workers spend an excess of forty percent of their working lives exposed to roofing asphalt (AREC, 1999). Asphalt is the residuum produced by the distillation of crude petroleum. Performance specifications, and not chemical composition, direct asphalt production. To meet specifications, asphalt may be processed by being air blown or solvent precipitated. Also, the products of other refining processes may be blended with asphalt to achieve the desired performance specifications. Therefore, the exact chemical composition of asphalt depends on the chemical complexity of the original crude petroleum plus the manufacturing processes involved. Asphalt is employed in three different roofing systems: shingles or roll roofing, built-up roofing (BUR), and modified bitumen roofing. Worker exposures to asphalt fumes and vapors are only

of concern in those roofing systems that involve the heating of asphalt: BUR and modified bitumen systems (NIOSH, 2003a). Mopping grade asphalt is typically delivered to the construction site in solid form and then is heated in a roofing kettle prior to application. Alternately, it is delivered in a liquid state in a temperature-controlled tanker. Potential worker exposures are related to the operation of the kettle and application on the rooftop. The recommended temperature for mopping-grade roofing asphalts is 330-445 °F (166-229 °C) (NIOSH, 2003b). To achieve this temperature at the point of application, the temperature of the asphalt in the kettle has been reported to be as high as 600°F (316°C). Hot asphalt is then delivered to the roof through a metal supply line from the kettle (or tanker). It is emptied into a rooftop storage container called a “hot lugger”. This hot asphalt is then accessed either manually by workers who pour it into carts and perform the mopping operation or by automated systems that pour and apply the mopping layer. In the manual method, workers apply the asphalt with hand-held mopping tools and open-topped containers for the liquid material; making worker exposures a concern in the kettle operation and manual mopping functions of these roofing operations.

Chemical Constituents of Roofing Asphalt

Roofing asphalt vapors and fumes have been found to differ from those associated with paving operations because of the higher temperatures involved in roofing asphalt application and the differences in the manufacturing process. While there have been few field studies to characterize the constituents of asphalt fumes and vapors, a small number of laboratory studies have analyzed the emissions. Thayer (Thayer et al, 1981) and Niemeier (Niemeier, et al, 1988) performed GC/MS analysis on laboratory emissions of asphalt generated at 232°C and 316°C. The results indicated that emissions consisted mainly of two-and four-ring polycyclic aromatic hydrocarbons (PAHs) with small amounts of five-ring PAHs. Notable is the presence of the carcinogenic substances: benz(a)anthracene, BaP, and dibenzanthracenes. Also using GC/MS, Lunsford and Cooper (1989) characterized the chemical classes present in roofing asphalt fractions separated by high performance liquid chromatography (HPLC). Several sulfur-containing and oxygen-containing polycyclic aromatic compounds were identified. Little is known about the toxicity of these

compounds; however, they bear structural similarity to known mutagens and carcinogens (NIOSH, 2001). Also found were unalkylated isomers of chrysene and benz(a)anthracene, identified as probable human carcinogens by the IARC (Malaiyandi, 1982). Naphthalene, a major constituent in both laboratory studies, is classified by IARC as possibly carcinogenic to humans and animals (IARC, 1985). In a field study of roofing asphalt exposure, Hatjian reported on the GC/MS analysis of personal-breathing-zone air samples of asphalt fumes collected at several work sites (Hatjian et al, 1997). Two- and three-ring PAHs accounted for 84-94% of the PAH exposures. Naphthalene accounted for 80% to 96% of the measured PAHs. Other PACs detected were acenaphthene, phenanthrene, pyrene, benz(a)anthracene, and BaP. BaP was detected in 25-28% of the samples. In its Hazard Review of the Health Effects of Occupational Exposure to Asphalt, NIOSH recommended additional research to characterize worker exposures to BaP, chrysene, benz(a)anthracene, and the S- and O-PACs (NIOSH, 2001). Noted was the fact that asphalt fumes generated at higher temperatures, such as those in roofing operations, are probably more hazardous than fumes generated at lower temperatures.

Health Effects of Roofing Asphalt Exposure

Asphalt fumes and vapors have been associated with both acute and chronic health effects. Studies concerning the acute toxic effects of exposure to asphalt fumes have repeatedly found symptoms of irritation of the mucous membranes of the upper airways, the eyes, and the skin. Mucosal irritation tends to be mild and transient in nature. Skin irritation, pruritus, and occasional rashes have been reported (Norseth et al, 1991). Asphalt-related dermal photosensitization has been suggested, but requires additional investigation to substantiate (Hervin and Emmett, 1976). In contrast to pavers, studies of roofers have generally demonstrated an excess number of lung cancer cases. A meta-analysis of epidemiologic studies of roofers indicates an excess of lung cancer and neoplasm of the buccal cavity and pharynx among roofers (Partanen and Boffetta, 1994). This 1994 comprehensive review of epidemiologic studies of asphalt workers found that the relative risk for lung cancer was elevated for asphalt roofers, but not for highway pavers. There have been several cohort mortality studies of roofers exposed to asphalt fumes. A retrospective study of members of the United Slate, Tile, and Composition

Roofers, Damp and Waterproof Workers' Association, found that asphalt roofer lung cancer mortality increased with time in job (Engholm et al, 1991). The Swedish Construction Industry's Organization for Working Environment, Safety, and Health conducted a study of cancer mortality and incidence among construction workers, including 704 roofers. Increased mortality for cancer of the lung was observed among roofers. Data from experimental studies in animals and cultured mammalian cells indicate that laboratory-generated roofing asphalt fume condensates are genotoxic and cause skin tumors in mice when applied dermally (McFall et al, 1984). In its Hazard Evaluation report, NIOSH concludes that roofing asphalt fumes are a potential occupational carcinogen, based on the review of epidemiologic studies and the evidence of known carcinogenic constituents in characterization studies (NIOSH, 2001).

PtD Approaches for Asphalt Vapor/Fume Control

The main exposing activities are those associated with the asphalt kettle operation and rooftop application. There are some engineering control options available to reduce the exposure to fumes and vapors: delivery to the rooftop via tanker rather than kettle and hot lugger system; lidded rooftop containers such as hot luggers, mechanical asphalt spreaders, and felt-laying machines; insulated kettles; insulated hot luggers; fume-suppressing asphalt; and local-exhaust ventilation systems. Delivery of the hot asphalt to the job site can be accomplished via a tanker, which would eliminate the on-site kettle operation for handling and heating the asphalt. Roof application exposures can be reduced through the use of lidded and insulated distribution systems. Asphalt fume emissions from the kettle can be reduced by maintaining a constant temperature and preventing the release of fumes. A variety of thermostatically controlled heating systems are available to maintain a set asphalt temperature in the kettle. Kettles are often constructed of double walls with thermal insulation. They may also have double lids to maintain temperature and control exposures. Local exhaust ventilation (LEV) emission capture systems have been introduced for use on kettles to evacuate fumes from the headspace inside the kettle. Automated mechanical systems for rooftop application of mopping layers can be used to remove the human operator. Low-fuming asphalt has been developed to reduce the emission of asphalt fumes from the kettle. A polymer additive to the asphalt separates and forms a floating skim on

the surface of the hot asphalt. Initial field studies indicate that the skim dramatically reduces fume emissions (NIOSH, 2003a).

Survey:

PtD Usage in Concrete, Masonry, and Asphalt Roofing Trades

METHODS

Overall Strategy

Sample

Since the decision to adopt PtD control technologies is ultimately made at management levels of construction organizations, this project characterized the management perspective on PtD controls and the barriers to their adoption. As a part of the standardized calling protocol, telephone bank operators asked to speak with the person in charge of making purchasing decisions.

The populations of interest in this study are all firms in the United States engaged in the following construction trades: masonry, concrete, asphalt roofing, and welding. Due to the highly decentralized nature of the construction industry, a non-probability sampling strategy was employed in this project, with a convenience sample population consisting of those firms that are members of major trade associations in these sectors. Sample power calculations cannot be performed, since this study is to be descriptive, rather than experimental, and since non-probability sampling, rather than random sampling, is to be employed (since the normality assumption cannot be met). Therefore, the sample population is the entire membership of the associations, described below. Key trade organizations served as the census sample population of interest. To evaluate PtD control use in the concrete and masonry trade sectors, the members of the following trade organizations were contacted for interview: the Mason Contractors Association of America (MCAA)(n=700), the Concrete Sawing and Drilling Association (CSDA)(n=541), and the American Concrete Pavement Association (ACPA)(n=4000). The Mason Contractors Association of America is the foremost national trade association representing masonry contractors and suppliers in national legislative and political affairs, codes and standards composition, workforce development, education, market promotion, and general industry advocacy. The association's membership of over 1000 firms accounts for \$2 billion in masonry sales annually. CSDA is an international association of over 550 contractor, manufacturer, distributor, and affiliated member companies from the concrete construction and renovation industry. Its mission is to promote professional sawing and drilling contractors and their methods. The American Concrete Pavement Association is the national trade association for the concrete pavement industry. The ACPA has over 450 member firms, which represent over 4,000 management-level contacts.

To evaluate PtD control use in the asphalt roofing trade, the members of the National Roofing Contractors Association (NRCA)(n=4000) were contacted for interview. NRCA is one of the construction industry's most respected trade associations and the voice and leading authority in the roofing industry for information, education, technology, and advocacy. Founded in 1886, NRCA is a nonprofit association that represents all segments of the roofing industry supply chain including contractors, manufacturers, distributors, architects, consultants, engineers, building owners, and city, state, and government agencies. NRCA has more than 4,000 members from all 50 states and 53 countries and is affiliated with 97 local, state, regional, and international roofing contractor associations. NRCA contractor members range in size from companies with less than \$1 million in annual sales volumes (40 percent of the current membership) to large commercial contractors with annual sales volumes of more than \$20 million. More than half perform both residential and commercial roofing work and more than one-third have been in business for more than a quarter of a century.

Survey Instruments

Previously validated survey instruments, which were developed to assess PtD trends in the drywall-finishing trade sector, were adapted for the trades of interest in the proposed work. The survey instruments were constructed to measure constructs of the PtD ARM and to predict Adoption Readiness. While the original instruments contain specific PtD innovations for the drywall trade, in the current work the instruments was revised to include the PtD innovations listed in Table I. To provide evidence of content validity, the revised instruments was subjected to cognitive testing, reliability, and validity testing, described below. Adopting methods previously developed the principal investigator (Young-Corbett and Nussbaum, 2009), survey instruments were designed to gather information about control practices used in the trade sectors of interest. One instrument was used for both Concrete and Masonry trades, since the hazards and controls are similar to operations in both. Scaled and open-ended survey items solicited information about the key constructs. The survey instrument was developed by a workgroup through a defined process that incorporates input from Subject Matter Experts (SMEs) and validation through cognitive interview techniques. The survey instrument development process is described in this section. To design the survey instrument, a workgroup was established. The group was composed of the Principal Investigator, survey research specialists from the Center for Survey Research, and the project's graduate research assistants. The group performed the following functions associated with instrument development:

identification of survey items based on the project's PtD innovations of interest (Table I), development of a draft survey instrument, solicitation of input from SMEs, incorporation of SME feedback into a second draft, performance of cognitive interviews for instrument validation, and incorporation of cognitive interview feedback into a final survey instrument.

Table I: PtD Innovations of Interest by Trade Sector

Trade Sector	PtD Innovation
Concrete/Masonry	Ventilated tools
Concrete/Masonry	Wet-method systems
Concrete/Masonry	Isolation systems
Concrete/Masonry	Sweeping compound
Concrete/Masonry	Material substitution
Asphalt Roofing	Tanker delivery systems
Asphalt Roofing	Hot luggers, mechanical spreaders, felt-laying machines
Asphalt Roofing	Insulated kettles, insulated hot luggers
Asphalt Roofing	Fume-suppressing asphalt
Asphalt Roofing	Local-exhaust ventilation
Welding	Local-exhaust ventilation: high-vacuum low-volume, high-volume low-vacuum, and fume-extracting nozzle
Welding	Low-smoke wire

Data Collection

Telephone interview protocols were reviewed and approved by the Institutional Review Board of Virginia Tech. All telephone calls were made in a standardized manner, using a computer-assisted telephone interviewing software system (Sawtooth Technologies' WinCATI 4.2®). Each interviewer collecting data for the survey participated in a project-specific training session. Interviews began with a brief summary of project objectives, a review of informed consent information, and an assurance that firm identity would never be linked to responses and that only aggregate data would be published. Interviews were conducted with either firm owners or general managers. Scaled interview items were recorded in a Likert-type scale format. Responses to open-ended questions were transcribed verbatim. All calls were monitored by a phone bank supervisor to ensure data accuracy and adherence to proper interviewing protocol. Each of the firms were contacted until reached, or to a maximum of nine attempts. These attempts were made at different times of day and on different days of the week.

Analysis

The analysis of the data consisted of three phases: 1) survey instrument validation, 2) descriptive statistics of scaled survey items, and 3) content analysis of open-ended responses. These methods are described in detail, below.

Survey Instrument Validation

The development of the survey instruments was performed via a rigorous process, involving three phases: 1) construct operationalization, 2) cognitive testing, and 3) validation and reliability testing. Each of these phases is described in detail, below.

Construct Operationalization

Previously Validated Scales and Indices

The survey instruments for the proposed project were adapted from an instrument previously developed by the PI's research team: the PtD ARM Employer Instrument. Because the PtD ARM was constructed from three well-established conceptual models, the Technology Acceptance Model (TAM), the Diffusion of Innovation Model (DOI), and the Health Belief Model (HBM), the research team searched the extant scholarly literature for scales, indices, and survey instruments based upon these models. Only those instruments that had been subjected to rigorous development and validation protocols were selected for review. Additionally, only those that seemed most applicable for adaptation to the present use were selected for the final set. These included Champion's Health Belief Model scales(7), Parasuraman's Technology Readiness Index (TRI)(8), The Self Efficacy Scale (SES) by Sherer and Maddux(9), Robinson's Trust Scale(10), Venkatesh's Technology Acceptance Model instrument(11), and Armenakis' Change Readiness Scale(3). Champion's HBM scale contains items to measure perceived risk, benefits, barriers, and motivation. The TRI contains items pertaining to the constructs of "readiness" and "innovativeness", which were adapted for the current instrument. The SES contains items pertaining to self-efficacy, which were adapted for the PtD ARM instrument. Specifically, items pertaining to the constructs "personal control", "competency", and "self-esteem" were selected for inclusion. Robinson's Trust Scale contained items pertaining to organizational trust and a worker's trust in the employer. Venkatesh was the first to operationalize the TAM constructs: "perceived ease of use" and "perceived usefulness" and that author's instrument has been subjected to rigorous field validation by numerous investigators. And, Armenakis' scale contains specific items for assessing "adoption readiness". From these previously validated instruments, items pertaining to the PtD ARM constructs were selected for adaptation and modification into language that pertains to the drywall finishing trade sector.

Initial Item Set

The previously developed instrument contains 20 items, which were intended to measure the following constructs: perceived health risk, trust in organization, trust in technology, adoption readiness, perceived ease of use, and perceived usefulness. In the current work, these items were adapted to the four trade sectors of interest: concrete, masonry, asphalt roofing, and welding.

Card Sort Technique

Construct operationalization of the new items were further evaluated through item-construct correspondence. The item-construct correspondence will be evaluated through an evaluative, closed, card-sorting procedure. In a closed card sort, participants are provided with a deck of cards which contain phrases and a predetermined set of category names. They then assign the index cards to these fixed categories. This helps reveal the degree to which the participants agree on which cards belong under each category. Closed sorting is evaluative; it is typically used to judge whether a given set of category names provides an effective way to organize a given collection of content. In this study, a group of ten participants will individually perform the card sorting technique. These participants will be graduate students in the human factors engineering program at Virginia Tech. Each will be given a stack of cards with one survey instrument item printed on each. On the table will be papers indicating the constructs of the PtD ARM model. Participants will be asked to place the cards on the construct name they feel most closely matches the statement on the card. All construct categories will be assigned a numerical code, so that inter-rater reliability can be assessed using Krippendorff's alpha coefficient. Those instrument items having reliability of $\alpha \leq 0.80$ will be removed from the item pool or revised and re-tested.

Cognitive Testing.

Subject Matter Expert (SME) Review

The initial item pool was reviewed by two types of SME: those with expertise in survey instrument development and those with expertise in construction operations. Researchers in the Virginia Tech Center for Survey research will comprise the first set of SME reviewers. These SMEs will possess knowledge of psychometrics and design of surveys, tests, and instruments. They will review the item pool and make comments on any problematic items, in terms of item construction. The second set of SMEs will be employers and workers in the masonry, asphalt

roofing, and welding trades. They will be asked to review the items and identify any problems in language, terminology, understandability, and relevance.

Probing Cognitive Interviews

In this phase of the study, members of the Myers-Lawson School of Construction Industry Board and workers from Southwestern Virginia were asked to participate in cognitive interviews. Probing cognitive interviewing is the technique that has increasingly come into favor by cognitive researchers. After the interviewer asks the survey question and the participant answers, the interviewer asks for additional information relevant to the question, or to the specific answer given. In general, the interviewer "probes" further into the basis for the response.

Validation and Reliability Testing

This phase of instrument development included specific assessment of convergent validity and discriminant validity and the prerequisite unidimensionality and reliability.

Unidimensionality was evaluated via confirmatory factor analysis (CFA) to test the construct measurement model. A goodness of fit index (GFI) exceeding 0.90 indicates strong unidimensionality. In the case of complex model development exploratory phase, as is the case in the current paper, some authors have suggested that an index as low as 0.80 can be used as a minimum threshold for unidimensionality.⁽¹⁴⁾ Therefore, in the current study, a GFI index greater than or equal to 0.80 was considered to be an indication of item unidimensionality. Once the unidimensionality of scales is established, an assessment of the statistical reliability is necessary before any further validation. Cronbach's reliability coefficient (α) was employed, with the 0.60 threshold for Cronbach's alpha to be set as the threshold of reliability. To assess the convergent validity of the PtD ARM instrument items on the model constructs, the study employed the Bentler-Bonett coefficient (Δ). Values of Δ between 0.80 and 0.90 were considered to be acceptable, though a value greater than 0.90 demonstrates strong convergent validity. Finally, discriminant validity was assessed following the tests for convergent validity, using the Average Interscale Correlation Test, the Item-total Correlations Test, and the Percent Variance Extracted test.

CONSTRUCT	UNIDIM	RELIABILITY	CONV.	DISCRIMINANT VALIDITY						
	GFI	α	Δ	Interscale Correlation		Item-to-total Correlations			Percent Variance	
				AVISC	α -AVISC	SCITC	NSCITC	SCIC-NSCIC	PVE	PVE/100 – AVISC ²
PR	0.91	0.847	0.980	0.434	0.423	0.645	0.355	0.290	59.01	0.402
TO	0.88	0.701	0.810	0.442	0.367	0.575	0.361	0.214	52.01	0.325
TT	0.82	0.798	0.856	0.305	0.441	0.579	0.247	0.332	66.40	0.571
SE	0.98	0.964	0.917	0.466	0.332	0.622	0.384	0.238	63.89	0.422
PEOU	0.89	0.816	0.950	0.336	0.574	0.798	0.270	0.528	78.94	0.677
PU	0.95	0.869	0.965	0.295	0.669	0.899	0.237	0.662	87.70	0.790
PU-Q	0.96	0.721	0.884	0.443	0.385	0.606	0.365	0.241	55.14	0.355
PU-P	0.97	0.824	0.945	0.428	0.388	0.624	0.353	0.271	60.22	0.419
AR	0.94	0.943	0.913	0.344	0.430	0.697	0.369	0.328	66.09	0.455

Descriptive Statistics of Scaled Survey Items

Means and standard deviations for all scaled survey items were calculated and summarized graphically using scatter and bar chart techniques. Principal component factor analysis with varimax rotation was employed to identify key model constructs in each of the trade sectors. The PtD conceptual model was tested for concurrent and predictive validity, using correlation and multivariate analysis procedures. Multinomial logistic regression was used to identify leading independent predictors of “adoption readiness”. Predictors will include the PtD ARM model constructs: perception of health risk, trust in technology, perceived ease of use, perceived usefulness, and firm demographic information. Odds ratios for each predictor variable will indicate the effect size on the readiness to adopt.

Content Analysis of Open-ended Items

The survey instruments contained several open-ended items, designed to solicit information about: 1) current usage rates of PtD approaches, 2) perceived barriers to adoption, 3) perceived benefits from adoption. Responses to open-ended survey items were analyzed using content analysis procedures. Codes that are both exhaustive and mutually exclusive will be established for each set of open-ended responses. These codes will then be assigned to responses by two independent coders with education in conducting human factors research, and who have been trained on the particular coding definitions and process. Inter-coder reliability will be calculated for each set of codes, using Krippendorff's alpha, with an acceptance criterion of $\alpha \geq 0.80$.

RESULTS

Usage Trends for Ventilated Concrete and Masonry Tools

Exposure to concrete or masonry dust poses a potential health risk to workers.

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	STRONGLY AGREE	59.000	35.329	35.329	35.329
	SOMEWHAT AGREE	73.000	43.713	43.713	79.042
	SOMEWHAT DISAGREE	25.000	14.970	14.970	94.012
	STRONGLY DISAGREE	9.000	5.389	5.389	99.401
	DK/RF	1.000	0.599	0.599	100.000
	Total	167.000	100.000	100.000	

Concrete or masonry dust can cause severe health effects.

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	STRONGLY AGREE	60.000	35.928	35.928	35.928
	SOMEWHAT AGREE	63.000	37.725	37.725	73.653
	SOMEWHAT DISAGREE	25.000	14.970	14.970	88.623
	STRONGLY DISAGREE	10.000	5.988	5.988	94.611
	DK/RF	9.000	5.389	5.389	100.000
	Total	167.000	100.000	100.000	

How familiar are you with dust collection equipment?

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	VERY FAMILIAR	57.000	34.132	34.132	34.132
	SOMEWHAT FAMILIAR	72.000	43.114	43.114	77.246
	SLIGHTLY FAMILIAR	22.000	13.174	13.174	90.419
	NOT AT ALL FAMILIAR	16.000	9.581	9.581	100.000
	Total	167.000	100.000	100.000	

How often do your employees use dust collection equipment?

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	ALWAYS	43.000	25.749	28.477	28.477
	REGULARLY	45.000	26.946	29.801	58.278
	SOMETIMES	27.000	16.168	17.881	76.159
	RARELY	23.000	13.772	15.232	91.391
	NEVER	13.000	7.784	8.609	100.000
	Total	151.000	90.419	100.000	
Missing	System	16.000	9.581		
Total		167.000	100.000		

Dust collection equipment is beneficial to the health of my workers.

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	STRONGLY AGREE	88.000	52.695	63.768	63.768
	SOMEWHAT AGREE	40.000	23.952	28.986	92.754
	SOMEWHAT DISAGREE	3.000	1.796	2.174	94.928
	STRONGLY DISAGREE	1.000	0.599	0.725	95.652
	DK/RF	6.000	3.593	4.348	100.000
	Total	138.000	82.635	100.000	
Missing	System	29.000	17.365		
Total		167.000	100.000		

Dust collection equipment reduces concrete or masonry dust exposure.

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	STRONGLY AGREE	90.000	53.892	65.217	65.217
	SOMEWHAT AGREE	40.000	23.952	28.986	94.203
	SOMEWHAT DISAGREE	4.000	2.395	2.899	97.101
	STRONGLY DISAGREE	1.000	0.599	0.725	97.826
	DK/RF	3.000	1.796	2.174	100.000
	Total	138.000	82.635	100.000	
Missing	System	29.000	17.365		
Total		167.000	100.000		

I anticipate my company will use, or continue to use, dust collection equipment in our work.

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	STRONGLY AGREE	94.000	56.287	68.116	68.116
	SOMEWHAT AGREE	34.000	20.359	24.638	92.754
	SOMEWHAT DISAGREE	4.000	2.395	2.899	95.652
	STRONGLY DISAGREE	2.000	1.198	1.449	97.101
	DK/RF	4.000	2.395	2.899	100.000
	Total	138.000	82.635	100.000	
Missing	System	29.000	17.365		
Total		167.000	100.000		

How often do your employees use wet-method systems?

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	ALWAYS	60.000	35.928	42.553	42.553
	REGULARLY	55.000	32.934	39.007	81.560
	SOMETIMES	15.000	8.982	10.638	92.199
	RARELY	5.000	2.994	3.546	95.745
	NEVER	4.000	2.395	2.837	98.582
	DK/RF	2.000	1.198	1.418	100.000
	Total	141.000	84.431	100.000	
Missing	System	26.000	15.569		
Total		167.000	100.000		

How familiar are you with isolation systems?

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	VERY FAMILIAR	16.000	9.581	9.581	9.581
	SOMEWHAT FAMILIAR	46.000	27.545	27.545	37.126
	SLIGHTLY FAMILIAR	9.000	5.389	5.389	42.515
	NOT AT ALL FAMILIAR	96.000	57.485	57.485	100.000
	Total	167.000	100.000	100.000	

How often do your employees use isolation systems?

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	ALWAYS	1.000	0.599	1.408	1.408
	REGULARLY	8.000	4.790	11.268	12.676
	SOMETIMES	20.000	11.976	28.169	40.845
	RARELY	28.000	16.766	39.437	80.282
	NEVER	14.000	8.383	19.718	100.000
	Total	71.000	42.515	100.000	
Missing	System	96.000	57.485		
Total		167.000	100.000		

How often do your employees use sweeping compound?

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	ALWAYS	6.000	3.593	8.696	8.696
	REGULARLY	15.000	8.982	21.739	30.435
	SOMETIMES	11.000	6.587	15.942	46.377
	RARELY	19.000	11.377	27.536	73.913
	NEVER	17.000	10.180	24.638	98.551
	DK/RF	1.000	0.599	1.449	100.000
	Total	69.000	41.317	100.000	
Missing	System	98.000	58.683		
Total		167.000	100.000		

What business factors would affect the way you address fume-control on your projects: Insurance Premiums.

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Not Selected	65.000	38.922	38.922	38.922
	Selected	102.000	61.078	61.078	100.000
	Total	167.000	100.000	100.000	

What business factors would affect the way you address fume-control on your projects: Government Regulations.

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Not Selected	30.000	17.964	17.964	17.964
	Selected	137.000	82.036	82.036	100.000
	Total	167.000	100.000	100.000	

What business factors would affect the way you address fume-control on your projects: Productivity.

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Not Selected	57.000	34.132	34.132	34.132
	Selected	110.000	65.868	65.868	100.000
	Total	167.000	100.000	100.000	

Usage Trends for PtD Asphalt Roofing Tools

Exposure to asphalt fumes poses a potential health risk to workers.

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	STRONGLY AGREE	25.000	12.563	12.563	12.563
	SOMEWHAT AGREE	76.000	38.191	38.191	50.754
	SOMEWHAT DISAGREE	50.000	25.126	25.126	75.879
	STRONGLY DISAGREE	43.000	21.608	21.608	97.487
	DK/RF	5.000	2.513	2.513	100.000
	Total	199.000	100.000	100.000	

Asphalt fumes can cause severe health effects.

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	STRONGLY AGREE	29.000	14.573	14.573	14.573
	SOMEWHAT AGREE	62.000	31.156	31.156	45.729
	SOMEWHAT DISAGREE	41.000	20.603	20.603	66.332
	STRONGLY DISAGREE	48.000	24.121	24.121	90.452
	DK/RF	19.000	9.548	9.548	100.000
	Total	199.000	100.000	100.000	

How familiar are you with liquid asphalt tanker delivery systems?

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	VERY FAMILIAR	51.000	25.628	25.628	25.628
	SOMEWHAT FAMILIAR	36.000	18.090	18.090	43.719
	SLIGHTLY FAMILIAR	22.000	11.055	11.055	54.774
	NOT AT ALL FAMILIAR	89.000	44.724	44.724	99.497
	DK/RF	1.000	0.503	0.503	100.000
	Total	199.000	100.000	100.000	

How often do your employees use liquid asphalt tanker delivery systems?

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	ALWAYS	4.000	2.010	3.670	3.670
	REGULARLY	9.000	4.523	8.257	11.927
	SOMETIMES	12.000	6.030	11.009	22.936
	RARELY	23.000	11.558	21.101	44.037
	NEVER	61.000	30.653	55.963	100.000
	Total	109.000	54.774	100.000	
Missing	System	90.000	45.226		
Total		199.000	100.000		

Liquid asphalt tanker delivery systems reduce asphalt fume exposure.

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	STRONGLY AGREE	21.000	10.553	43.750	43.750
	SOMEWHAT AGREE	17.000	8.543	35.417	79.167
	SOMEWHAT DISAGREE	1.000	0.503	2.083	81.250
	STRONGLY DISAGREE	4.000	2.010	8.333	89.583
	DK/RF	5.000	2.513	10.417	100.000
	Total	48.000	24.121	100.000	
Missing	System	151.000	75.879		
Total		199.000	100.000		

I anticipate my company will use, or continue to use, liquid asphalt tanker delivery systems in our work.

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	STRONGLY AGREE	22.000	11.055	45.833	45.833
	SOMEWHAT AGREE	11.000	5.528	22.917	68.750
	SOMEWHAT DISAGREE	4.000	2.010	8.333	77.083
	STRONGLY DISAGREE	5.000	2.513	10.417	87.500
	DK/RF	6.000	3.015	12.500	100.000
	Total	48.000	24.121	100.000	
Missing	System	151.000	75.879		
Total		199.000	100.000		

How familiar are you with hot luggers, mechanical spreaders, and felt-laying machines?

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	VERY FAMILIAR	106.000	53.266	53.266	53.266
	SOMEWHAT FAMILIAR	41.000	20.603	20.603	73.869
	SLIGHTLY FAMILIAR	10.000	5.025	5.025	78.894
	NOT AT ALL FAMILIAR	40.000	20.101	20.101	98.995
	DK/RF	2.000	1.005	1.005	100.000
	Total	199.000	100.000	100.000	

How often do your employees use hot luggers, mechanical spreaders, or felt-laying machines?

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	ALWAYS	22.000	11.055	14.013	14.013
	REGULARLY	31.000	15.578	19.745	33.758
	SOMETIMES	29.000	14.573	18.471	52.229
	RARELY	39.000	19.598	24.841	77.070
	NEVER	36.000	18.090	22.930	100.000
	Total	157.000	78.894	100.000	
Missing	System	42.000	21.106		
Total		199.000	100.000		

Hot luggers, mechanical spreaders, and felt-laying machines reduce asphalt fume exposure.

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	STRONGLY AGREE	22.000	11.055	18.182	18.182
	SOMEWHAT AGREE	46.000	23.116	38.017	56.198
	SOMEWHAT DISAGREE	28.000	14.070	23.140	79.339
	STRONGLY DISAGREE	16.000	8.040	13.223	92.562
	DK/RF	9.000	4.523	7.438	100.000
	Total	121.000	60.804	100.000	
Missing	System	78.000	39.196		
Total		199.000	100.000		

I anticipate my company will use, or continue to use, hot luggers, mechanical spreaders, and felt-laying machines in our work.

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	STRONGLY AGREE	85.000	42.714	70.248	70.248
	SOMEWHAT AGREE	26.000	13.065	21.488	91.736
	SOMEWHAT DISAGREE	4.000	2.010	3.306	95.041
	STRONGLY DISAGREE	4.000	2.010	3.306	98.347
	DK/RF	2.000	1.005	1.653	100.000
	Total	121.000	60.804	100.000	
Missing	System	78.000	39.196		
Total		199.000	100.000		

How often do your employees use insulated kettles or insulated hot luggers?

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	ALWAYS	26.000	13.065	18.182	18.182
	REGULARLY	30.000	15.075	20.979	39.161
	SOMETIMES	26.000	13.065	18.182	57.343
	RARELY	19.000	9.548	13.287	70.629

Insulated kettles or insulated hot luggers are beneficial to the health of my workers.

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	STRONGLY AGREE	42.000	21.106	41.584	41.584
	SOMEWHAT AGREE	32.000	16.080	31.683	73.267
	SOMEWHAT DISAGREE	10.000	5.025	9.901	83.168
	STRONGLY DISAGREE	4.000	2.010	3.960	87.129
	DK/RF	13.000	6.533	12.871	100.000
	Total	101.000	50.754	100.000	
Missing	System	98.000	49.246		
Total		199.000	100.000		

How familiar are you with low-fuming asphalt?

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	VERY FAMILIAR	58.000	29.146	29.146	29.146
	SOMEWHAT FAMILIAR	63.000	31.658	31.658	60.804
	SLIGHTLY FAMILIAR	14.000	7.035	7.035	67.839
	NOT AT ALL FAMILIAR	63.000	31.658	31.658	99.497
	DK/RF	1.000	0.503	0.503	100.000
	Total	199.000	100.000	100.000	

How often do your employees use low-fuming asphalt?

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	ALWAYS	22.000	11.055	16.296	16.296
	REGULARLY	19.000	9.548	14.074	30.370
	SOMETIMES	20.000	10.050	14.815	45.185
	RARELY	31.000	15.578	22.963	68.148
	NEVER	43.000	21.608	31.852	100.000
	Total	135.000	67.839	100.000	
Missing	System	64.000	32.161		
Total		199.000	100.000		

Low-fuming asphalt reduces asphalt fume exposure.

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	STRONGLY AGREE	48.000	24.121	52.174	52.174
	SOMEWHAT AGREE	31.000	15.578	33.696	85.870
	SOMEWHAT DISAGREE	5.000	2.513	5.435	91.304
	STRONGLY DISAGREE	2.000	1.005	2.174	93.478
	DK/RF	6.000	3.015	6.522	100.000
	Total	92.000	46.231	100.000	
Missing	System	107.000	53.769		
Total		199.000	100.000		

I anticipate my company will use, or continue to use, low-fuming asphalt in our work.

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	STRONGLY AGREE	48.000	24.121	52.174	52.174
	SOMEWHAT AGREE	35.000	17.588	38.043	90.217
	SOMEWHAT DISAGREE	2.000	1.005	2.174	92.391
	STRONGLY DISAGREE	4.000	2.010	4.348	96.739
	DK/RF	3.000	1.508	3.261	100.000
	Total	92.000	46.231	100.000	
Missing	System	107.000	53.769		
Total		199.000	100.000		

How familiar are you with kettle fume guards?

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	VERY FAMILIAR	43.000	21.608	21.608	21.608
	SOMEWHAT FAMILIAR	47.000	23.618	23.618	45.226
	SLIGHTLY FAMILIAR	14.000	7.035	7.035	52.261
	NOT AT ALL FAMILIAR	92.000	46.231	46.231	98.492
	DK/RF	3.000	1.508	1.508	100.000
	Total	199.000	100.000	100.000	

I anticipate my company will use, or continue to use, kettle fume guards in our work.

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	STRONGLY AGREE	33.000	16.583	60.000	60.000
	SOMEWHAT AGREE	16.000	8.040	29.091	89.091
	SOMEWHAT DISAGREE	3.000	1.508	5.455	94.545
	STRONGLY DISAGREE	3.000	1.508	5.455	100.000
	Total	55.000	27.638	100.000	
Missing	System	144.000	72.362		
Total		199.000	100.000		

What business factors would affect the way you address fume-control on your projects: Insurance Premiums.

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Not Selected	83.000	41.709	41.709	41.709
	Selected	116.000	58.291	58.291	100.000
	Total	199.000	100.000	100.000	

What business factors would affect the way you address fume-control on your projects: Government Regulations.

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Not Selected	57.000	28.643	28.643	28.643
	Selected	142.000	71.357	71.357	100.000
	Total	199.000	100.000	100.000	

What business factors would affect the way you address fume-control on your projects: Productivity.

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Not Selected	91.000	45.729	45.729	45.729
	Selected	108.000	54.271	54.271	100.000
	Total	199.000	100.000	100.000	

What business factors would affect the way you address fume-control on your projects: Worker Safety.

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Not Selected	47.000	23.618	23.618	23.618
	Selected	152.000	76.382	76.382	100.000
	Total	199.000	100.000	100.000	

Have you seen an increase in projects specifying fume-control methods?

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	YES	71.000	35.678	35.678	35.678
	NO	126.000	63.317	63.317	98.995
	DK/RF	2.000	1.005	1.005	100.000
	Total	199.000	100.000	100.000	

In the past year what percent of your work specifies using fume-control methods?

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	0-25%	142.000	71.357	71.357	71.357
	26-50%	20.000	10.050	10.050	81.407
	51-75%	6.000	3.015	3.015	84.422
	76-100%	14.000	7.035	7.035	91.457
	DK/RF	17.000	8.543	8.543	100.000
	Total	199.000	100.000	100.000	

Q4y.Please tell me why your employees do not use dust collection equipment?

Respondent# Response

- 10 Don't have it for our application.
- 15 Availability expense.
- 37 Just don't use it.
- 38 Don't deal directly with concrete and concrete dust; service provider for the industry.
- 51 No reason for me to use them because I build buildings. We use water when we cut.
- 85 Most of work is small.
- 97 Using wet blade/saw.
- 99 Use wet method.
- 124 Dust mask, respirator.

- 131 We don't cut concrete. O'Brien international is the management company that manages certain concrete companies.
- 136 Outside most of the time, use it inside.
- 140 Use wet methods systems mostly.
- 194 Use wet methods.

Q16y. Please tell me why your employees do not use wet-method systems?

<u>Respondent#</u>	<u>Response</u>
36	Works mostly with steel.
38	Don't use it because they are service provider.
73	Because they are at a concrete plant, it is messy.
78	Don't know.
186	Don't think it's necessary.

Q28y. Please tell me why your employees do not use isolation systems?

<u>Respondent#</u>	<u>Response</u>
12	We use wet systems, and dry when outside.
38	Service provider; don't use.
49	Most of the work is out in the open so that's not an issue.
70	Don't have a need for it.
87	Not always an option.
92	Usually work outside.
97	Not necessary.
109	We normally use wet method systems.
110	Not familiar.
148	They are out in the open.
185	Because of the work they do, cannot isolate.

Q40y. Please tell me why your employees do not use sweeping compound?

<u>Respondent#</u>	<u>Response</u>
3	Not sure why they use it...certain jobs necessitate using it because of the sweeping compound, especially if they are doing work on a building that is occupied.
8	Being a brick lane contractor, we are well before clean up stages.
12	Big guys lay brick, not sweep floors.
13	Don't sweep that much; pick up debris with shovels instead.
48	We work with industrial jobsites so the clean up happens after we leave the site.
70	Don't have a need for it.
79	It is not necessary. It's for indoor and they mostly work outdoor.
81	They don't do their own clean up.
83	Wet method is primarily used.
89	Don't do any sweeping.
90	Just don't do much sweeping.
104	80% of the time working in the dirt so it wouldn't make sense. When working on concrete surfaces we use sand in order prevent adhesion of the mortar to the concrete.
108	We don't sweep.
129	We are outside, outside construction.
178	They don't need to use it for the purpose of their work.
194	Wet methods.

Publications Resulting from Project

Journal Articles

1. **Weidman, J.E.***, Young-Corbett, D.E., Koebel, C.T. (2015). Prevention through Design (PtD): A macro-ergonomic conceptual approach to risk reduction. *Institute of Industrial Engineers Transactions on Occupational Ergonomics and Human Factors*. (in press)
2. **Dickerson, D.E.** (submitted) Prevention through Design (PtD): Health Hazards in Concrete and Masonry Operations. *International Journal of Construction Education and Research*.
3. **Weidman, J.E.***, Young-Corbett, D.E., Koebel, C.T. (2015). Prevention through Design Adoption Readiness Model (PtD ARM): An Integrated Conceptual Model. *Work: A Journal of Prevention, Assessment, and Rehabilitation*. (in press)
4. **Young-Corbett, D.E.** (2014). Prevention through Design (PtD): Health Hazards in Asphalt Roofing. *Journal of Construction Engineering and Management*. 140(9). (<http://ascelibrary.org/doi/abs/10.1061/%28ASCE%29CO.1943-7862.0000892>)
5. **Weidman, J.E.***, Young-Corbett, D.E., Koebel, C.T. (2015). An intervention to improve purchasing decision-maker perceptions of ventilated tools. *Journal of Construction Engineering and Management*. (<http://ascelibrary.org/doi/abs/10.1061/%28ASCE%29CO.1943-7862.0000961>

Book Chapter

Young-Corbett, DE: [submitted January 2012, accepted July 2012] Prevention through Design: Eliminating Occupational and Environmental Risk through Design of Equipment, Work, and Systems. *Chapter in: The Handbook of Industrial and Systems Engineering*, 2nd Edition. Taylor and Francis, CRC Press. Boca Raton, FL. Badiru, AB, editor.

Conference Proceedings

1. Goldberg, A. and Young-Corbett, D. (May 19, 2014). Adoption Readiness of Prevention through Design (PtD) Control in Concrete, Masonry, and Asphalt Roofing. Poster session presented at the Construction Research Congress, Atlanta, GA.
2. Goldberg, A. and Young-Corbett, D. (August 19, 2014). Decision Making in Commercial Construction. Presented at the Organizational Design and Management conference, Copenhagen, Denmark.

Inclusion of Gender and Minority Participants

Study Title: Prevention through Design Adoption Readiness
Total Enrollment: 172 **Protocol Number:** FWA00000572
Grant Number: 5 U60 OH009761-03 Project ID 658

PART A. TOTAL ENROLLMENT REPORT: Number of Subjects Enrolled to Date (Cumulative)				
Ethnic Category	Females	Males	Sex/Gender Unknown or Not	Total
Hispanic or Latino	0	84	0	84 **
Not Hispanic or Latino	0	88	0	88
Unknown (individuals not reporting ethnicity)	0	0	0	0
Ethnic Category: Total of All Subjects*	0	172	0	172 *
Racial Categories				
American Indian/Alaska Native	0	0	0	0
Asian	0	0	0	0
Native Hawaiian or Other Pacific Islander	0	0	0	0
Black or African American	0	0	0	0
White	0	172	0	172
More Than One Race	0	0	0	0
Unknown or Not Reported	0	0	0	0
Racial Categories: Total of All Subjects*	0	172	0	172 *
PART B. HISPANIC ENROLLMENT REPORT: Number of Hispanics or Latinos Enrolled to Date (Cumulative)				
Racial Categories	Females	Males	Sex/Gender Unknown or Not	Total
American Indian or Alaska Native	0	0	0	0
Asian	0	0	0	0
Native Hawaiian or Other Pacific Islander	0	0	0	0
Black or African American	0	0	0	0
White	0	84	0	84
More Than One Race	0	0	0	0
Unknown or Not Reported	0	0	0	0
Racial Categories: Total of Hispanics or	0	84	0	84 **

Inclusion of Children

Not applicable

Materials Available for Other Investigators

All study methods and results have been disseminated to the scholarly community via the publications described herein.

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Appendix: Validated Survey Instruments

Hello, my name is _____ and I'm calling from Virginia Tech on behalf of the Industrial and Systems Engineering department. As a member of the concrete or masonry industry, we are interested in your feelings about your work with concrete or masonry. There are no right or wrong answers; we are looking only for your individual opinion. All answers will remain anonymous.

1

**Please indicate your level of agreement with the following statements:
Exposure to concrete or masonry dust poses a potential health risk to workers. Do you strongly agree, somewhat agree, somewhat disagree, or strongly disagree?**

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

2

Concrete or masonry dust can cause severe health effects.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

3

How familiar are you with dust collection equipment? Would you say very familiar, somewhat familiar, slightly familiar, or not at all familiar?

VERY FAMILIAR

SOMEWHAT FAMILIAR

SLIGHTLY FAMILIAR

NOT AT ALL FAMILIAR (skip to Q15)

DK/RF (skip to Q15)

4

How often do your employees use dust collection equipment? Would you say always, regularly, sometimes, rarely, or never?

ALWAYS

REGULARLY

SOMETIMES

RARELY

NEVER

DK/RF

If 4 IS NEVER/DK/RF: Please tell me why your employees do not use dust collection equipment? (Skip to Q15)

5

Please indicate your level of agreement with the following statements: I trust dust collection equipment will get the job done well.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

6

I feel dust collection equipment work well.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

7

Dust collection equipment is beneficial to the health of my workers.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

8

Dust collection equipment reduces concrete or masonry dust exposure.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

9

Dust collection equipment is a useful tool for working with concrete or masonry products.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

10

Dust collection equipment improves job performance.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

11

More work gets done when using dust collection equipment.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

12

Dust collection equipment allows my workers to accomplish more work than would otherwise be possible.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

13

I anticipate my company will use, or continue to use, dust collection equipment in our work.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

14

My company looks forward to using, or continuing to use, dust collection equipment.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

15

How familiar are you with wet-method systems?

VERY FAMILIAR

SOMEWHAT FAMILIAR

SLIGHTLY FAMILIAR

NOT AT ALL FAMILIAR (skip to Q27)

DK/RF (skip to Q27)

16

How often do your employees use wet-method systems?

ALWAYS

REGULARLY

SOMETIMES

RARELY

NEVER

DK/RF

If 16 IS NEVER/DK/RF: Please tell me why your employees do not use wet-method systems? (skip to Q27)

17

Please indicate your level of agreement with the following statements: I trust wet-method systems will get the job done well. Do you strongly agree, somewhat agree, somewhat disagree, or strongly disagree?

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

18

I feel wet-method systems work well.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

19

Wet-method systems are beneficial to the health of my workers.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

20

Wet-method systems reduce concrete or masonry dust exposure.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

21

Wet-method systems are useful equipment for working with concrete or masonry products.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

22

Wet-method systems improve job performance.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

23

More work gets done when using wet-method systems.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

24

Wet-method systems allow my workers to accomplish more work than would otherwise be possible.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

25

I anticipate my company will use, or continue to use, wet-method systems in our work.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

26

My company looks forward to using or continuing to use wet-method systems.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

27

Isolation systems entail either isolating the workers from dust producing activities, isolating dust producing activities from the workers, or enclosure systems for certain tools. How familiar are you with isolation systems?

VERY FAMILIAR

SOMEWHAT FAMILIAR

SLIGHTLY FAMILIAR

NOT AT ALL FAMILIAR (skip to Q39)

DK/RF (skip to Q39)

28

How often do your employees use isolation systems?

ALWAYS

REGULARLY

SOMETIMES

RARELY

NEVER

DK/RF

If 28 IS NEVER/DK/RF: Please tell me why your employees do not use isolation systems? (skip to Q39)

29

Please indicate your level of agreement with the following statements: I trust isolation systems will get the job done well. Do you strongly agree, somewhat agree, somewhat disagree, or strongly disagree?

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

30

I feel isolation systems work well.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

31

Isolation systems are beneficial to the health of my workers.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

32

Isolation systems reduce concrete or masonry dust exposure.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

33

Isolation systems are useful methods for working with concrete or masonry products.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

34

Isolation systems improve job performance.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

35

More work gets done when using isolation systems.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

36

Isolation systems allow my workers to accomplish more work than would otherwise be possible.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

37

I anticipate my company will use, or continue to use, isolation systems in our work.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

38

My company looks forward to using or continuing to use isolation systems.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

39

How familiar are you with sweeping compound?

VERY FAMILIAR

SOMEWHAT FAMILIAR

SLIGHTLY FAMILIAR

NOT AT ALL FAMILIAR (skip to QI)

DK/RF (skip to QI)

40

How often do your employees use sweeping compound?

ALWAYS

REGULARLY

SOMETIMES

RARELY

NEVER

DK/RF

If 40 IS NEVER/DK/RF: Please tell me why your employees do not use sweeping compound? (skip to QI)

41

Please indicate your level of agreement with the following statements: I trust sweeping compound will get the job done well. Do you strongly agree, somewhat agree, somewhat disagree, or strongly disagree?

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

42

I feel sweeping compound works well.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

43

Sweeping compound is beneficial to the health of my workers.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

44

Sweeping compound reduces concrete or masonry dust exposure.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

45

Sweeping compound is a useful material for working with concrete or masonry products.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

46

I anticipate my company will use, or continue to use, sweeping compound in our work.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

47

More work gets done when using sweeping compound.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

48

Sweeping compound allows my workers to accomplish more work than would otherwise be possible.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

49

I anticipate my company will use, or continue to use, sweeping compound in our work.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

My company looks forward to using or continuing to use sweeping compound.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

I. What business factors would affect the way you address dust-control on your projects...

(CHECK ALL THAT APPLY) Insurance Premiums? Government Regulations? Productivity? Worker Safety? Other? (please specify the other business factors:)

II. Have you seen an increase in projects specifying dust-control methods?

Yes No

III. In the past year what percent of your work specifies using dust -control methods? 0-25% 26-50% 51-75% 76-100%

IV. Concrete or masonry dust-control technologies currently available are dust collection equipment, wet-method systems, isolation systems, and sweeping compound. What are some other dust-control methods that you know about or have used?

V. If you could imagine an ideal way of controlling concrete or masonry dust that does not currently exist, what would it be and why?

VI. Now just a few final questions about you. What is your job title?

VII. How many full-time employees work for you?

VIII. In what year were you born?

IX. Gender.

Hello, my name is _____ and I'm calling from Virginia Tech on behalf of the Industrial and Systems Engineering department. As a member of the asphalt roofing industry, we are interested in your feelings about your work with hot asphalt. There are no right or wrong answers; we are looking only for your individual opinion. All answers will remain anonymous.

1

**Please indicate your level of agreement with the following statements:
Exposure to asphalt fumes poses a potential health risk to workers. Do you strongly agree, somewhat agree, somewhat disagree, or strongly disagree?**

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

2

Asphalt fumes can cause severe health effects.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

3

How familiar are you with liquid asphalt tanker delivery systems? Would you say very familiar, somewhat familiar, slightly familiar, or not at all familiar?

VERY FAMILIAR

SOMEWHAT FAMILIAR

SLIGHTLY FAMILIAR

NOT AT ALL FAMILIAR (skip to Q15)

DK/RF (skip to Q15)

4

How often do your employees use liquid asphalt tanker delivery systems? Would you say always, regularly, sometimes, rarely, or never?

ALWAYS

REGULARLY

SOMETIMES

RARELY

NEVER

DK/RF

If 4 IS NEVER/DK/RF: Please tell me why your employees do not use liquid asphalt tanker delivery systems? (Skip to Q15)

5

Please indicate your level of agreement with the following statements: I trust liquid asphalt tanker delivery systems will get the job done well.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

6

I feel liquid asphalt tanker delivery systems work well.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

7

Liquid asphalt tanker delivery systems are beneficial to the health of my workers.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

8

Liquid asphalt tanker delivery systems reduce asphalt fume exposure.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

9

Liquid asphalt tanker delivery systems are useful equipment for working with asphalt.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

10

Liquid asphalt tanker delivery systems improve job performance.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

11

More work gets done when using liquid asphalt tanker delivery systems.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

12

Liquid asphalt tanker delivery systems allow my workers to accomplish more work than would otherwise be possible.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

13

I anticipate my company will use, or continue to use, liquid asphalt tanker delivery systems in our work.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

14

My company looks forward to using or continuing to use liquid asphalt tanker delivery systems.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

15

How familiar are you with hot luggers, mechanical spreaders, and felt-laying machines?

VERY FAMILIAR

SOMEWHAT FAMILIAR

SLIGHTLY FAMILIAR

NOT AT ALL FAMILIAR (skip to Q27)

DK/RF (skip to Q27)

16

How often do your employees use hot luggers, mechanical spreaders, or felt-laying machines?

ALWAYS

REGULARLY

SOMETIMES

RARELY

NEVER

DK/RF

If 16 IS NEVER/DK/RF: Please tell me why your employees do not use hot luggers, mechanical spreaders, or felt-laying machines?

17

Please indicate your level of agreement with the following statements: I trust hot luggers, mechanical spreaders, and felt-laying machines will get the job done well. Do you strongly agree, somewhat agree, somewhat disagree, or strongly disagree?

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

18

I feel hot luggers, mechanical spreaders, and felt-laying machines work well.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

19

Hot luggers, mechanical spreaders, and felt-laying machines are beneficial to the health of my workers.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

20

Hot luggers, mechanical spreaders, and felt-laying machines reduce asphalt fume exposure.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

21

Hot luggers, mechanical spreaders, and felt-laying machines are useful equipment for working with asphalt.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

22

Hot luggers, mechanical spreaders, and felt-laying machines improve job performance.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

23

More work gets done when using hot luggers, mechanical spreaders, and felt-laying machines.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

24

Hot luggers, mechanical spreaders, and felt-laying machines allow my workers to accomplish more work than would otherwise be possible.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

25

I anticipate my company will use, or continue to use, hot luggers, mechanical spreaders, and felt-laying machines in our work.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

26

My company looks forward to using or continuing to use hot luggers, mechanical spreaders, and felt-laying machines.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

27

How familiar are you with insulated kettles or insulated hot luggers?

VERY FAMILIAR

SOMEWHAT FAMILIAR

SLIGHTLY FAMILIAR

NOT AT ALL FAMILIAR (skip to Q39)

DK/RF (skip to Q39)

28

How often do your employees use insulated kettles or insulated hot luggers?

ALWAYS

REGULARLY

SOMETIMES

RARELY

NEVER

DK/RF

If 28 IS NEVER/DK/RF: Please tell me why your employees do not use insulated kettles or insulated hot luggers? (skip to Q39)

29

Please indicate your level of agreement with the following statements: I trust insulated kettles or insulated hot luggers will get the job done well. Do you strongly agree, somewhat agree, somewhat disagree, or strongly disagree?

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

30

I feel insulated kettles or insulated hot luggers work well.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

31

Insulated kettles or insulated hot luggers are beneficial to the health of my workers.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

32

Insulated kettles or insulated hot luggers reduce asphalt fume exposure.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

33

Insulated kettles or insulated hot luggers are useful equipment for working with asphalt.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

34

Insulated kettles or insulated hot luggers improve job performance.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

35

More work gets done when using insulated kettles or insulated hot luggers.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

36

Insulated kettles or insulated hot luggers allow my workers to accomplish more work than would otherwise be possible.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

37

I anticipate my company will use, or continue to use, insulated kettles or insulated hot luggers in our work.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

38

My company looks forward to using, or continuing to use, insulated kettles or insulated hot luggers.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

39

Low-fuming asphalt, also known as odor-reducing asphalt, is a material which when heated in a kettle forms a skim on top. How familiar are you with low-fuming asphalt?

VERY FAMILIAR

SOMEWHAT FAMILIAR

SLIGHTLY FAMILIAR

NOT AT ALL FAMILIAR (skip to Q51)

DK/RF (skip to Q51)

40

How often do your employees use low-fuming asphalt?

ALWAYS

REGULARLY

SOMETIMES

RARELY

NEVER

DK/RF

If 40 IS NEVER/DK/RF: Please tell me why your employees do not use low-fuming asphalt? (skip to Q51)

41

Please indicate your level of agreement with the following statements: I trust low-fuming asphalt will get the job done well. Do you strongly agree, somewhat agree, somewhat disagree, or strongly disagree?

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

42

I feel low-fuming asphalt works well.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

43

Low-fuming asphalt is beneficial to the health of my workers.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

44

Low-fuming asphalt reduces asphalt fume exposure.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

45

Low-fuming asphalt is a useful material.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

46

Low-fuming asphalt improves job performance.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

47

More work gets done when using low-fuming asphalt.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

48

Low-fuming asphalt allows my workers to accomplish more work than would otherwise be possible.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

49

I anticipate my company will use, or continue to use, low-fuming asphalt in our work.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

50

My company looks forward to using or continuing to use low-fuming asphalt.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

51

How familiar are you with kettle fume guards?

VERY FAMILIAR

SOMEWHAT FAMILIAR

SLIGHTLY FAMILIAR

NOT AT ALL FAMILIAR (skip to I)

DK/RF (skip to QI)

52

How often do your employees use kettle fume guards?

ALWAYS

REGULARLY

SOMETIMES

RARELY

NEVER

DK/RF

If 52 IS NEVER/DK/RF: Please tell me why your employees do not use kettle fume guards? (skip to I)

53

Please indicate your level of agreement with the following statements: I trust kettle fume guards will get the job done well. Do you strongly agree, somewhat agree, somewhat disagree, or strongly disagree?

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

54

I feel kettle fume guards work well.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

55

Kettle fume guards are beneficial to the health of my workers.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

56

Kettle fume guards reduce asphalt fume exposure.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

57

Kettle fume guards are useful equipment for working with asphalt.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

58

Kettle fume guards improve job performance.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

59

More work gets done when using kettle fume guards.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

60

Kettle fume guards allow my workers to accomplish more work than would otherwise be possible.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

61

I anticipate my company will use, or continue to use, kettle fume guards in our work.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

62

My company looks forward to using or continuing to use kettle fume guards.

STRONGLY AGREE

SOMEWHAT AGREE

SOMEWHAT DISAGREE

STRONGLY DISAGREE

DK/RF

I. What business factors would affect the way you address fume-control on your projects...

(CHECK ALL THAT APPLY) Insurance Premiums? Government Regulations? Productivity? Worker Safety? Other? (please specify the other business factors:)

II. Have you seen an increase in projects specifying fume-control methods?

Yes No

III. In the past year what percent of your work specifies using fume-control methods? 0-25% 26-50% 51-75% 76-100%

IV. Asphalt roofing fume-control technologies currently available are liquid asphalt tanker delivery systems, hot luggers or mechanical spreaders or felt-laying machines, insulated kettles or insulated hot luggers, fume-suppressing asphalt, and kettle fume guards. What are some other fume-control methods that you know about or have used?

V. If you could imagine an ideal way of controlling asphalt fumes that does not currently exist, what would it be and why?

VI. Now just a few final questions about you. What is your job title?

VII. How many full-time employees work for you?

VIII. In what year were you born?

IX. Gender.