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The benefits of an additional worker are task-dependent: Assessing low-back injury risks during prefabricated (panelized) wall construction

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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 and 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 an 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 and Mital, 1986; Lee, 2004) or increased (Lee, 2004; Mital and Motorwala, 1995) with teams composed of >2 members. Furthermore, during asymmetric lifting (i.e., loads are to the right or left of the body midline), 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 and 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.

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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 and 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 and 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 and 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 × 2.4 m), medium (1.2 m × 2.4 m) and large (3 m × 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 Fig. 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.

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,

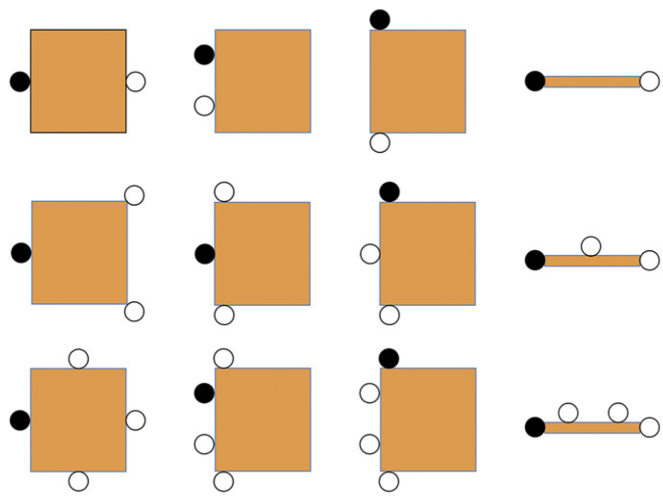

Fig. 1. Relative positions of each worker for each panel erection task, using 2, 3, or 4 workers (top to bottom). A filled circle denotes the participant (unfilled circles = experimenters).

Mass, and Task conditions. Each trial lasted about 10–20 s and was replicated twice, with ∼2 min rest between trials, while each session lasted ∼3 h.

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 cutoff 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 × Task interactions (Fig. 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 (Fig. 3).

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 × Size

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[a] (2308, 2782)**	77 (61, 97)	**41.3[a] (38.3, 43.5)**	**2.0[b] (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[c] (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)

[a] Indicates that there are also significant Additional worker × Task interactions.
[b] Indicates that there are also significant interaction effects of additional worker with mass and Size.
[c] Indicates that there are also significant Additional worker × Size interactions.

interaction ($p = 0.0403$). Similar to the Additional worker × 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 and Barrett, 2002) and peak spinal compression forces (Dennis and Barrett, 2002; Marras et al., 1999; Mital and 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 and 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 (Fig. 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

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)

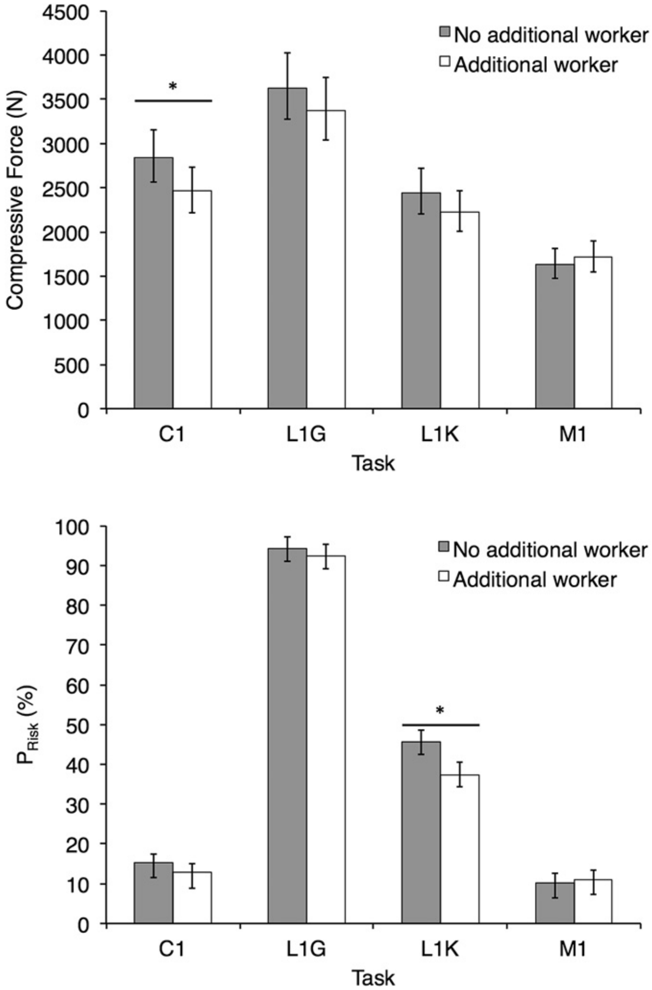

Fig. 2. Interaction effects of task and additional worker on spinal compressive force (F_z; Top) and the probability of membership in a group at high risk of a low back disorder (P_{Risk}; Bottom). Significant reductions from including an additional worker are indicated by *, and error bars indicate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

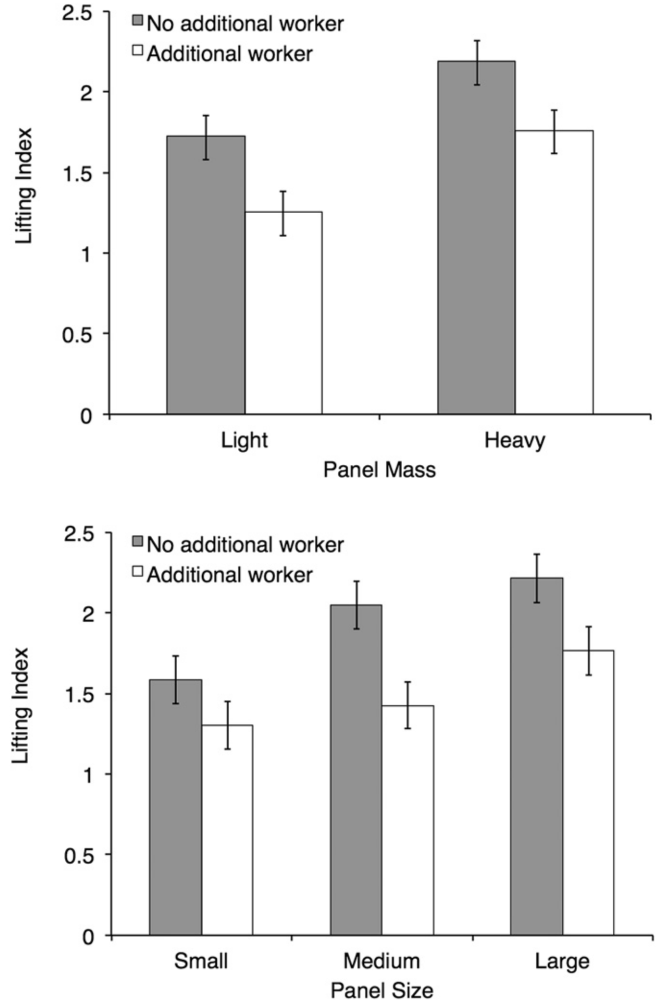

Fig. 3. Interactive effects of Mass and Additional worker (Top) and Size and Additional worker (Bottom) on Lifting Index. Within a given mass and size, all decreases with an Additional worker were significant. Error bars indicate 95% confidence intervals.

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 and 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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