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Prevention strategies for musculoskeletal disorders among high-risk occupational groups

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PREVENTION STRATEGIES FOR MUSCULOSKELETAL DISORDERS AMONG HIGH-RISK OCCUPATIONAL GROUPS

by

Alysha Rose Meyers

An Abstract

Of a thesis submitted in partial fulfillment
of the requirements for the Doctor of
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ABSTRACT

The objective of the three studies in this dissertation was to improve methods to prevent musculoskeletal disorders among workers in high-risk occupations.

The first two studies, Strain Index (SI) Studies I & II, addressed this problem by better characterizing the performance of a commonly used observational method of estimating potentially hazardous biomechanical exposures, the SI. The SI combines measures of several biomechanical risk factors into a single value (SI score). Strain Index scores are usually categorized into four ordinal SI "risk categories." In Strain Index Study I, multivariate survival analysis models were compared to evaluate the predictive validity of the original SI risk category cut-points to a new set of empirically derived cut-point values among 276 manufacturing workers. The results from this prospective study indicated that the empirically derived cut-points were a better predictor of incident hand-arm symptoms than the original cut-points, especially among women.

In Strain Index Study II, Aim 1, exposures to forceful exertions, repetition and non-neutral wrist posture estimated with SI methods were compared to analogous exposures estimated with alternate methods. Statistically significant associations between separate methods designed to assess specific risk factors were observed only for those measuring non-neutral wrist posture. In Aim 2, a multivariate survival analysis model examining associations between incident hand-arm symptoms and biomechanical exposures estimated with the SI was compared to a model examining associations between incident hand-arm symptoms and biomechanical exposures estimated with separate estimates of biomechanical risk factors. Results favored the SI risk category metric to characterize biomechanical exposures compared to separate measures of exposure.

The third study, light-weight block (LWB) Intervention Study, was a repeated measures laboratory study of 25 bricklayers performed to estimate the effect of block weight (LWB vs. standard-weight block (SWB)) and course height on low back disorder (LBD) risk factor exposure. Mixed-effect models showed that LWB was associated with reduced exposure for percent time spent in sagittal flexion > 30°, lifting rate, LBD risk probability score, and non-dominant upper trapezius muscle activity. Bricklaying at ankle or chest heights was generally associated with higher exposure to risk factors than bricklaying at knuckle height.

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Graduate College
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CERTIFICATE OF APPROVAL

PH.D. THESIS

This is to certify that the Ph.D. thesis of

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Essentially, all models are wrong, but some are useful.

George E. P. Box
Empirical model-building and response surfaces

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CHAPTER 1. INTRODUCTION

Work-related musculoskeletal disorders (MSDs) of the back and upper extremities are common among US workers and result in pain, disability, and substantial cost to workers and employers (Bureau of Labor Statistics, 2002; 2007). Work-related MSDs include carpal tunnel syndrome; tendonitis of the hand, wrist, elbow, and shoulder; and low back pain and can affect muscles, nerves, tendons, tendon sheaths, joints, intervertebral discs and blood vessels. The incidence of MSDs is not equally distributed across occupational groups. For example, upper extremity MSDs (UEMSDs) are more frequent among manufacturing workers and low back MSDs (LBDs) are more frequent among construction workers when compared to all workers in private industry (Bureau of Labor Statistics, 2006, 2007; U.S. Department of Labor, 2001). Over the past few decades, work-related MSDs have become an important public health concern.

The premise of a traditional public health model for MSD prevention is to use epidemiologic evidence as a basis for prevention strategies targeted towards high-risk occupations, jobs, and tasks (Smith, 2001). The research conducted for this dissertation focused on several aspects of the public health model: 1) evaluating and improving methods used to identify and measure MSD risk factors, 2) quantifying associations between risk factors and MSDs, and 3) quantifying the effect of an intervention on exposure to biomechanical risk factors.

1.1. Musculoskeletal Disorders

In 2000, MSDs cost between $13 billion and $54 billion in workers' compensation claims in addition to lost workdays, decreased productivity, and other direct and indirect costs (NORA Musculoskeletal Disorders Team, 2001). The Bureau of Labor Statistics (BLS) of the U.S. Department of Labor reported that in 2006, MSDs accounted for 30% of reported occupational illnesses resulting in lost work days in private industry (Bureau of Labor Statistics, 2007).

High-risk occupational groups such as manufacturing workers and bricklayers experience a greater incidence of MSDs compared to other occupational groups. For example, compared to a sedentary occupation such as administrative service workers, the incidence of LBDs is higher among construction workers and the incidence of upper extremity MSDs is higher among manufacturing workers. (Arndt et al., 2005; Bureau of Labor Statistics, 2006, 2007; Courtney, Matz, & Webster, 2002; Dimov et al., 2000; Elders & Burdorf, 2004; Everett, 1999; Guo, Chang, Yeh, Chen, & Guo, 2004; Snashall, 2005; U.S. Department of Labor, 2001). In 2006, the incidence rate (IR) of nonfatal occupational illnesses and injuries involving days away from work (per 10,000 full-time workers) caused by lifting among construction workers was 22.2 and the incidence rate for injuries caused by repetitive motion among manufacturing workers was 10.3. These rates are high compared to all workers in private industry (IR=16.3 for lifting; IR=4.1 for repetitive motion) or administrative workers (IR=8.4 for lifting; IR=2.4 for repetitive motion) (Bureau of Labor Statistics, 2006). Among all construction specialty trade workers, bricklayers had the fourth highest incidence rate (IR = 31.1) for lifting-related occupational illnesses and injuries.

1.2. Risk Factors for Musculoskeletal Symptoms and Disorders

The literature examining associations between occupational risk factors and MSDs has been reviewed and summarized (Bernard, 1997; National Research Council - Institute of Medicine, 2001). Forceful exertions, awkward postures, and repetitive motions of the hand and wrist were identified as important risk factors for UEMSDs (Bernard, 1997). Work-related lifting, forceful exertions, and awkward postures were identified as important risk factors for low back musculoskeletal disorders (LBDs) (Bernard, 1997). Furthermore, simultaneous exposure to more than one risk factor appears to increase risk to a greater extent than the sum of the individual risks alone.

1.3. Measuring Exposure to Risk Factors

Existing methods for assessing exposure to forceful exertions, awkward postures, and repetitive motions can be classified as direct, observational, and self-report (in order of decreasing degree of accuracy, complexity and cost). Direct methods produce quantitative exposure estimates but use sophisticated equipment, require greater expertise, are computationally intense, and can be impractical for use in field studies. Observational methods, on the other hand, are especially practical for field-based research with large sample sizes because they are relatively unobtrusive and inexpensive. Observational methods do not require sophisticated equipment but do require more judgment on the part of the observer and are more prone to observer bias than direct methods (Winkel & Mathiassen, 1994). A variety of self-reported methods (*e.g.* questionnaires) of variable validity and usefulness, are available to estimate biomechanical exposure. Virtually all self-report methods are inexpensive and, for exposures such as perceived exertion, may be the only method that provides an estimate of the domain to be measured. Besides tools that provide separate measures of force, repetition and non-neutral postures, a number of other methods, such as the Strain Index (SI), allow investigators to combine several risk factors into a single risk metric (Buchholz, Paquet, Punnett, Lee, & Moir, 1996; Hignett & McAtamney, 2000; Karhu, Härkönen, Sorvali, & Vepsäläinen, 1981; McAtamney & Corlett, 1993; Moore & Garg, 1995; Occhipinti, 1998; Rodgers, 1992).

Estimation of exposure to biomechanical risk factors is central to the three studies presented in this dissertation. In Chapters 2 and 3 of this dissertation, two prospective epidemiologic studies, Strain Index Studies I & II, were conducted to improve our understanding of a widely used exposure assessment tool. The Light-weight Block (LWB) Intervention Study presented in Chapter 4 of this dissertation was a laboratory simulation study that used direct exposure assessment tools to evaluate the efficacy of interventions on: 1) back posture, 2) lumbar kinematics, 3) LBD risk probability, and 4) back muscle activity. For the Light-weight Block Intervention Study, LBD risk probability was ascertained with a widely used empirical model, the *LBD risk model* (Marras, Allread, & Ried, 1999; Marras et al., 1993).

1.4. Intervention and Control Strategies for Prevention of MSDs

Engineering controls, administrative controls, and worker training are common approaches used for prevention of MSDs. Engineering controls involve redesign of the work environment to eliminate or reduce exposure to hazards. Engineering controls are generally the most effective intervention method because, unlike administrative controls, successful implementation is not dependent on behavioral compliance from individual workers or managers (Konz & Johnson, 2004). Design changes or substitutions of tools, equipment, materials, and work methods are all examples of engineering controls. The Light-weight Block Intervention Study in this dissertation (Chapter 4.) was a laboratory simulation study to evaluate the effect of an engineering control on exposure to risk factors for LBDs.

1.5. Background on the Strain Index (SI)

1.5.1. Review of SI Procedures

The Strain Index (SI) is a widely-used observational exposure assessment technique that combines measures of forceful exertion, repetition, and non-neutral wrist postures into a single upper extremity MSD risk metric (Bernard, 1997; Dempsey, McGorry, & Maynard, 2005; Jones & Kumar, 2006; Knox & Moore, 2001; Lee, Rafiq, Merrell, Ackerman, & Dennerlein, 2005; Moore & Garg, 1995; Moore, Rucker, & Knox, 2001; Moore, Vos, Stephens, Stevens, & Garg, 2006; National Research Council - Institute of Medicine, 2001; Rucker & Moore, 2002; Stephens, Vos, Stevens, & Moore, 2006; Stevens, Vos, Stephens, & Moore, 2004). To ascertain task-specific SI scores, trained observers rate the magnitude of workers' exposure for six SI "task parameters": intensity of exertion, hand-wrist posture, speed of work, percent duration of exertion, efforts per minute, and duration per day. To rate the magnitude of workers' exposure, the SI requires the observer to select the appropriate "rating criterion" category from an ordered list of categories established for each SI task parameter (Table 2.1.). For example, for the *intensity of exertion* task parameter, the five rating criterion are *Light*, *Somewhat Hard*, *Hard*, *Very Hard*, and *Near Maximal*.

For each SI task parameter, SI procedures assign each rating criterion a unitless numerical value (ranging from 0.25 to 13). In the peer-reviewed literature, these rating criterion values are referred to as SI task parameter "multipliers" (rating criterion values will be referred to as multipliers or multiplier values in this dissertation). The numerical multiplier values were established by Moore and Garg (1995) in an effort to account for the relative contribution to MSD risk of each rating criterion for each exposure parameter. The product of the six multiplier values is the task-specific SI score. Because the association between SI scores and UEMSDs may not be linear, Moore and Garg (1995) established four SI "risk categories": "Safe" (SI score ≤ 3), "Uncertain" (SI score < 3 and < 5), "Some risk" (SI score ≥ 5 and < 7), and "Hazardous" (SI score ≥ 7).

The procedures described above were developed to estimate the SI score (or risk category) for *single-task jobs*. For *multi-task jobs*, shift-specific SI scores can be calculated by combining task-specific SI scores using a procedure described in Chapter 2, Section 2.2.4.4.6. and Appendix D.

1.5.2. Terminology

In this dissertation, definitions for the terms *job, job rotation, task, exertion,* and *work element,* are consistent with terminology used in a recent article by Bao *et al*. (2009). Compared to the original SI paper by Moore and Garg there are some differences.

For the sake of clarity, common terms used to describe work that have been used with more than one meaning in the SI literature are defined in the text and are listed in a Glossary of Terms (Appendix A).

The terms *job* and *task* are two terms of particular importance for this dissertation. In this dissertation, the term *job* refers to all the work activities performed by an employee during a shift (Stephen Bao, Spielholz, Howard, & Silverstein, 2009). The term *task* refers to an essential part of a person's job that has a unique purpose (*e.g.* assemble basepan, braze basepan, secure lids onto the top of crates to prepare them for shipping, install gaskets on doors, program refrigerator water dispensers) (Stephen Bao et al., 2009).

1.5.3. Critique of the SI Literature

1.5.3.1. Hazard classifications

To make future adjustments to the SI scale, the investigators who developed the metric suggested that prospective studies should be done to test the task parameter rating criterion values and SI risk category cut-points presented in the original SI user guide (Moore & Garg, 1995). Although SI scores of ≥ 7 are considered 'Hazardous,' scores of > 30 are not uncommon and the maximum score is 1053 (Moore & Garg, 1995). According to Moore and Garg (1995), higher SI scores are difficult to interpret because the relationship between SI scores and UEMSD incidence rate was not linear in the sample they studied. Several ecologic, retrospective studies have reported that jobs meeting criteria for the "Hazardous" (≥ 7) SI risk category were associated with an increased risk of developing UEMSDs compared to lower SI risk categories (S. Bao, Howard, Spielholz, & Silverstein, 2006; Drinkaus, Sesek et al., 2003; Jones & Kumar, 2006). Four studies have found that the probability that a prevalent or incident upper extremity musculoskeletal outcome was observed among workers who performed jobs categorized as Hazardous, was consistently higher compared to the probability of observing a prevalent or incident outcome for jobs not categorized as Hazardous (S. Bao, Spielholz, Howard, & Silverstein, 2006; Hegmann, Garg, Moore, & Foster, 2006; Jones & Kumar, 2006; Joseph, Reeve, Kilduff, Hall-Counts, & Long, 2000). However, the magnitude of the association between the SI and incident or prevalent UEMSDs has been inconsistent in the literature (S. Bao, Spielholz et al., 2006; Hegmann et al., 2006; Jones & Kumar, 2006; Joseph et al., 2000). Two of those four studies did not examine incident UEMSD data and the other two were not published in peer-reviewed journals. Until now, no prospective studies were available in the peer-reviewed literature in which investigators evaluated the association between the original SI risk categories (using the original risk category cut-points) and incident hand-arm symptoms while controlling for personal, psychosocial, and work organization confounders. Additionally, despite considerable evidence that the current SI risk category cut-point values incorrectly categorize many jobs as hazardous, we were aware of no efforts to establish alternate cut-point values.

1.5.3.2. Epidemiologic evidence

The methods used by the SI developers to create the risk categories have some important limitations. Unlike most epidemiologic research in which individuals are the unit of analysis, the investigators who developed the SI used job (*e.g.* wizard knife operator, ham loader, grinder) as the unit of analysis, thus making the study ecological in design. The ecological design of the study was a major limitation because confounding by individual factors (*e.g.* age and gender) could not be controlled. Additionally the study conducted by the SI developers was retrospective in design. The SI developers defined a distal UEMSD case as any distal UEMSD reported on the employer's OSHA logs. Because there is some evidence that OSHA logs underestimate the actual number of MSDs, it is possible that the methods resulted in misclassification of some jobs (Morse et al., 2005). Powerful prospective study designs that used participant as the unit of analysis were conducted for Strain Index Studies I & II. The prospective study designs were a departure from prior studies that used job as the unit of analysis and retrospective health outcome data.

1.5.3.3. Modified SI methods for multi-task jobs

The original SI was designed to evaluate MSD risk among workers performing *single-exertion* jobs, not *multi-task jobs* (workers rotate between two or more tasks during a shift) or *multi-exertion tasks* (complex tasks). Recently, several modifications to the SI have been introduced to permit calculation of SI scores for multi-exertion (*e.g.* the Composite SI) and multi-task jobs (*i.e.*, the Cumulative Strain Index (CSI)) (Stephen Bao et al., 2009; 2006). Several alternate SI computation methods, such as the Composite SI and CSI are provided by Garg (2006), Bao *et al.* (2009), and Drinkaus *et al.* (2003). Although physiology, biomechanics, and epidemiology principles support the original SI, Composite SI, and CSI computation methods, these newly developed exposure estimation procedures have not been not well studied. Associations between prevalent or incident MSDs and SI exposures estimated with multi-exertion or multi-task SI computation methods have been examined in only a few studies (S. Bao, Spielholz et al., 2006; B. Silverstein et al., 2006). One conference proceedings paper has reported associations between incident carpal tunnel syndrome cases and SI scores calculated with the multi-task CSI method. Aside from that paper, we believe that SI Studies I & II are the first prospective studies to report associations between multi-task SI scores and the incidence of hand-arm symptoms.

1.6. LBDs among bricklayers

1.6.1. LBD Risk Factors among Bricklayers

Although bricklayers often work in awkward back postures or lift heavy materials, (Engholm & Holmström, 2005; Everett, 1999; Hartmann & Fleischer, 2005;

Jørgensen, Jensen, & Kato, 1991; van der Molen, Veenstra, Sluiter, & Frings-Dresen, 2004) physical constraints at construction worksites make interventions difficult to implement. Bricklayers' risk of developing LBD can be controlled by reducing the amount of heavy lifting performed (*e.g.* by reducing load, lift frequency, or length of moment arm) or exposure to awkward back postures (*e.g.* sagittal flexion, torso twisting).

1.6.2. Interventions for Bricklayers

Although many masonry tasks have not changed over several centuries (Anton, Rosecrance, Gerr, Merlino, & Cook, 2005), recent interventions have been designed to reduce heavy lifting. One such intervention is the substitution of heavy building materials (*e.g.,* Concrete Masonry Unit (CMU) block) with lighter weight alternatives, (*e.g.,* light-weight CMU block (LWB)). Three recent studies evaluated the effect of lighter weight building materials on risk factor exposure magnitude among masons (Anton et al., 2005; van Der Molen et al., 2008; Zellers & Simonton, 1997). Two were controlled laboratory studies to evaluate the effect of substituting LWB for heavier CMU block on risk factor exposure levels among bricklayers (Anton et al., 2005; Zellers & Simonton, 1997).

Zellers and Simonton compared handling a traditionally shaped (two closed-end cores) CMU block to handling an "A" shaped (one closed-end core and one opened-end core) LWB. The investigators found that estimated low back disc compression forces decreased with the LWB and no differences were observed between block type for back postures, lumbar kinematics, LBD high-risk group membership probability (LBD risk probability) (Marras & Allread, 2006; Marras et al., 1993), back muscle activity, and heart rate.

Anton *et al.* (2005) conducted a laboratory study using back muscle activity and heart rate measures to examine the effects of using LWB block compared to CMU blocks that were both traditionally shaped but different weights. Anton *et al.* (2005) observed reduced low back muscle activity for LWB in comparison to standard CMU block (SWB) at higher courses (rows). The researchers, however, did not evaluate back posture, lumbar kinematics, or LBD risk probability.

Further empirical evidence showing that LWB reduces exposure to LBD risk factors is needed to support the widespread substitution of LWB for SWB. The purpose of the laboratory simulation study presented in Chapter 4 of this dissertation was to quantify the effect of concrete block weight and wall height on: 1) back posture, 2) lumbar kinematics, 3) LBD risk probability, and 4) back muscle activity. Our first hypothesis was that, compared to ankle height (Course 1) or chest height (Course 7), laying block at knuckle height (Course 4) would be associated with lower (more favourable) exposure measures among metrics used to characterize lateral and twisting postures, back kinematics, sagittal moment, and LBD risk probability. Our second hypothesis was that, compared to SWB, laying LWB would be associated with more favourable exposures among all exposure metrics.

1.7. Significance of this research

Work-related MSDs result in substantial morbidity, disability, and cost. The overall goal of the studies presented in this dissertation was to prevent future MSDs. One factor that hinders efforts to mitigate exposure to physical hazards is the limited availability of rapid and low cost observational methods for assessing such exposures. *Strain Index Studies I & II* (Chapters 2, 3) addressed this problem by better characterizing the performance of a commonly used observational method of estimating biomechanical exposures. Also, there have been a limited number of laboratory studies that have evaluated available interventions for bricklayers. The *Light-weight Block Intervention Study* (Chapter 4) is significant because it provides evidence-based assessments of engineering controls for bricklayers. Over time, the results of these studies may allow researchers and occupational health practitioners to better identify hazardous jobs and target them for exposure reduction efforts.

The goals of the studies in this dissertation were to 1) evaluate the external validity of existing exposure assessment methods for UEMSDs, 2) suggest improvements to an existing exposure assessment method, and 3) evaluate the effect of an intervention for bricklayers on exposure to LBD risk factors.

1.8. Specific aims

1.8.1. Strain Index Studies I & II

Although the SI is widely used (Dempsey et al., 2005; Jones & Kumar, 2006; Knox & Moore, 2001; Lee et al., 2005; Moore & Garg, 1995; Moore et al., 2001; Moore et al., 2006; Rucker & Moore, 2002; Stephens et al., 2006; Stevens et al., 2004), empirical verification of the SI risk category structure is sparse. The purpose of Strain Index Studies I & II was to evaluate and improve the SI as an exposure assessment tool among manufacturing workers by using more powerful epidemiological methods and comparing the SI to alternate, separate estimates of exposure to biomechanical risk factors.

1.8.1.1. Specific aim for Strain Index Study I (Chapter 2)

The purpose of Strain Index Study I was 1) to develop an alternate set of risk category cut-points and 2) to compare associations between the original SI and the alternate SI risk categories and incident distal upper extremity musculoskeletal symptoms. Our expectation was that a risk category structure that predicts musculoskeletal outcome better than the originally proposed risk category structure can be established empirically.

Specific Aim: To compare the fit of a survival analysis model in which the association between SI risk category and incident hand-arm musculoskeletal symptoms was ascertained with the Original Structure to the fit of a survival analysis model in which the association between SI risk category and incident hand-arm musculoskeletal symptoms was ascertained with the Empirical Structure.

1.8.1.2. Specific aims for Strain Index Study II (Chapter 3)

The purpose of the project presented in Strain Index Study II was to compare a single metric of biomechanical risk, the SI risk category, to separate exposure assessment methods used to measure exposure to forceful exertions, repetition, and non-neutral wrist postures among manufacturing workers.

Specific aim 1: Compare measures of forceful exertion, repetition, and non-neutral wrist posture estimated with SI methods to measures of forceful exertion, repetition, and non-neutral wrist posture estimated with alternate exposure assessment methods.

Specific aim 2: To compare the effect of biomechanical exposures on incident hand-arm musculoskeletal symptoms adjusted for demographic and psychosocial confounders for a survival analysis model in which separate measures of force, repetition and non-neutral wrist posture were used to quantify exposures to biomechanical risk factors to a survival analysis model in which SI risk category was used to quantify exposures to biomechanical risk factors.

1.8.2. Specific Aim for LWB Intervention Study

Bricklayers are exposed regularly to biomechanical risk factors (*e.g.* heavy manual material handling and awkward back postures) at levels associated with LBDs (Engholm & Holmström, 2005; Everett, 1999; Hartmann & Fleischer, 2005; Jørgensen et al., 1991; van der Molen, Veenstra et al., 2004). Substituting lighter weight building materials may reduce the risk of LBDs by reducing the load on workers' backs. One such intervention is substitution of LWB (12.7 kg) for SWB (17.3 kg) (ASTM, 2003). The purpose of the LWB Intervention Study (Chapter 4) was to measure the effect of LWB on risk of LBDs among bricklayers.

Specific aim: The purpose of the present laboratory simulation study was to quantify the effect of concrete block weight and wall height on: 1) back posture, 2) lumbar kinematics, 3) LBD risk probability, and 4) back muscle activity.

CHAPTER 2. STRAIN INDEX STUDY I: COMPARING MODELS EXAMINING ASSOCIATIONS BETWEEN THE STRAIN INDEX AND INCIDENT HAND-ARM SYMPTOMS

2.1. Introduction

Many methods are available for assessing exposures to biomechanical risk factors for upper extremity musculoskeletal disorders (UEMSDs). Some of these methods allow investigators to combine several risk factors into a single risk metric (Buchholz et al., 1996; Hignett & McAtamney, 2000; Karhu et al., 1981; McAtamney & Corlett, 1993; Moore & Garg, 1995; Occhipinti, 1998; Rodgers, 1992). Few of these "combined" exposure assessment metrics have been validated using prospective epidemiologic methods that control for personal, psychosocial, and work organization factors.

The Strain Index (SI) is a widely used observation-based exposure assessment technique that combines measures of important upper extremity biomechanical risk factors (forceful exertion, repetition, and non-neutral wrist postures) into a single scale (Bernard, 1997; Dempsey et al., 2005; Jones & Kumar, 2006; Knox & Moore, 2001; Lee et al., 2005; Moore & Garg, 1995; Moore et al., 2001; Moore et al., 2006; National Research Council - Institute of Medicine, 2001; Rucker & Moore, 2002; Stephens et al., 2006; Stevens et al., 2004). Recently, to permit assessment of *multi-task jobs* modified SI computation methods, such as the Cumulative Strain Index (CSI), have been introduced (Stephen Bao et al., 2009; Garg, 2006). Multi-task jobs are common, especially among manufacturing workers, and include those jobs requiring rotation between two or more tasks. No convincing evidence is available supporting a specific method (*e.g.* time-weighted average, peak, or mean values) for quantifying the exposure experienced by workers performing multi-task jobs. Because multi-task jobs were included in this study, the CSI computation method was used to compute SI scores. To understand the CSI computation method it is first necessary to understand the SI. The following paragraphs will briefly summarize SI procedures relevant to understanding the CSI computation methods used in this study. Then, evidence of external validity of the SI will be presented prior to presenting the specific aim of the current study.

2.1.1. Review of SI Procedures

To ascertain task-specific SI scores, trained observers (SI raters) first rate the magnitude of workers' exposure to each of six SI "task parameters": intensity of exertion, hand/wrist posture, speed of work, percent duration of exertion, efforts per minute, and duration per day. To rate the magnitude of workers' exposure, the SI requires the observer to select the appropriate "rating criterion" category from a ordered list of categories established for each SI task parameter (Table 2.1.). For example, for the *intensity of exertion* task parameter, the five rating criterion are *Light, Somewhat Hard, Hard, Very Hard,* and *Near Maximal*.

For each SI task parameter, SI procedures assign each rating criterion an established unitless numerical value (ranging from 0.25 to 13). In the peer-reviewed literature, these rating criterion values are referred to as SI task parameter "multipliers" (rating criterion values will be referred to as multipliers or multiplier values in this dissertation). The numerical multiplier values were established by Moore and Garg (1995) to account for the relative contribution of each rating criterion for each exposure parameter. The product of the six multiplier values is the task-specific SI score. Because the association between SI scores and UEMSDs may not be linear, SI scores are usually categorized into four ordinal SI "risk categories." Based on results observed in one work environment, the SI classification method established by Moore and Garg used three cut-points to create the following four (Original) SI "risk categories": "Safe" (SI score ≤ 3), "Uncertain" (SI score < 3 and < 5), "Some Risk" (SI score ≥ 5 and < 7), and "Hazardous" (SI score ≥ 7) (Moore & Garg, 1995).

The procedures described above are used to estimate a SI score and assign a SI risk category for *single-task jobs*. For multi-task jobs, shift-specific SI scores are calculated by combining task-specific SI scores using one of the multi-task SI computation methods, such as the CSI, which is described in the Methods Section, below.

2.1.2. External Validity of the Strain Index

The SI is a widely used technique for measuring exposure to biomechanical risk factors. Compared to similar exposure assessment techniques, the internal and external validity of the SI has been widely studied. Several ecologic, retrospective studies have reported that jobs classified in the "Hazardous" (≥ 7) Original SI risk category were associated with an increased risk of developing UEMSDs compared to the lower SI risk categories (S. Bao, Howard et al., 2006; Drinkaus, Sesek et al., 2003; Jones & Kumar, 2006). Until now, no prospective studies have been conducted to evaluate the association between the Original SI risk category cut-points (Original Structure) and incident hand-arm symptoms while controlling for personal, psychosocial, and work organization confounders.

Although SI scores of ≥ 7 are considered "Hazardous," scores of > 30 are not uncommon and the theoretical maximum score is 1053 (Moore & Garg, 1995). Several recent studies suggest that the cut-point values used for the Original Structure may frequently misclassify non-hazardous jobs as hazardous (creating false positives) (S. Bao, Howard et al., 2006; Drinkaus, Sesek et al., 2003; Jones & Kumar, 2006). Despite wide acceptance of the Original Structure, empirical verification of the originally proposed cut-points is sparse. An alternate, empirically derived SI classification method (Empirical Structure) may be more predictive than the Original Structure. Until now, no studies have been published that provide evidence of associations between SI risk category and incident hand-arm symptoms or disorders.

The purpose of the current project was 1) to develop an alternate, empirical SI classification method (Empirical) and 2) to compare associations between incident hand-arm musculoskeletal symptoms and job risk categories when the categories were assigned using the Original SI classification method compared to using the Empirical SI classification method. Our expectation is that an Empirical Structure that predicts musculoskeletal outcome better than the Original Structure can be established empirically.

Specific Aim: To compare the fit of a survival analysis model in which the association between SI risk category and incident hand-arm musculoskeletal symptoms was ascertained with the Original Structure to the fit of a survival analysis model in which the association between SI risk category and incident hand-arm musculoskeletal symptoms was ascertained with the Empirical Structure.

2.2. Research Design and Methods

From 2004 to 2008, investigators at the University of Iowa (UI) performed a prospective cohort study of occupational risk factors for UEMSD among 387 household appliance manufacturing workers (the Iowa Study) ("Musculoskeletal disorders among manufacturing workers," Gerr, F., PI). The current study was a secondary analysis of previously collected data from the Iowa Study. Archived demographic, personal, occupational psychosocial, video, and hand-arm health outcome data collected for the Iowa Study were used for the analyses presented in this chapter. To ascertain the Strain Index data elements necessary for the current study, additional exposure information was extracted from archived video of study participants performing his/her task(s).

2.2.1. Study Population

All employees performing production work at a large manufacturing facility were eligible to participate in the Iowa Study. All Iowa Study participants were included in the current study unless they 1) met Iowa Study criteria for a symptom event at entry or 2) performed cyclic tasks with work cycles longer than six minutes.

2.2.2. Iowa Study Data Collection

2.2.2.1. Collection of Demographic, Personal, and Occupational Psychosocial Factors

Demographic, personal, and occupational psychosocial information was collected on two self-administered questionnaires completed by participants when they enrolled in the Iowa Study. The Job Content Questionnaire (JCQ) (Karasek, 1985; Karasek & Theorell, 1990) was used to estimate psychological job demands (i.e., demand), decision authority (i.e., control), coworker support, and supervisor support. As recommended by the JCQ developers, a four-category Job Strain variable was created: 1) low demand, high control (i.e., low strain job); 2) high demand, high control (i.e., active job); 3) low demand, low control (i.e., passive job); and 4) high demand, low control (i.e., high strain job). Negative affectivity (a person's tendency to experience unpleasant feelings) was assessed with the Positive Affectivity and Negative Affectivity Scales (PANAS-X) questionnaire (Crawford & Henry, 2004; Watson & Clark, 1994 (updated 1999); Watson, Clark, & A., 1988).

2.2.2.2. Daily Task Activities

Participants used pre-printed logs that were collected weekly to record information on 1) daily hours worked per task, 2) changes in work activities, 3) current work stress, 4) time spent performing non work-related hand intensive activities (*e.g.* gardening, playing video games), 5) time spent working at a second job, and 6) hand-arm symptoms.

2.2.2.3. Hand-Arm Symptoms

The Iowa Study categorized hand-arm symptoms with information about hand-arm symptom quality, severity, and duration that was recorded by participants using weekly diaries. Hand-arm symptoms met the Iowa Study symptom positive (Sx+) case definition if 1) pain, numbness, tingling, or burning symptoms were reported for the previous week, 2) symptom duration was at least 30 minutes, 3) reported pain level was at least 5 on a 0-10 visual analog scale or medication was used to alleviate pain, and 4) the symptoms were not attributed to an acute traumatic injury. The same Sx+ case definition used for the Iowa Study was used for the current study.

2.2.2.4. Video Observations

Ten to twenty minute videos of all study participants performing each of his or her tasks were recorded by Iowa Study investigators. During each recording, two digital video cameras were used to simultaneously record sagittal (side view) and frontal plane (anterior or posterior) views of participants. Split screen video clips were created by combining the sagittal and frontal plane (anterior or posterior) video recordings for each participant. In the laboratory, split screen video clips were viewed for each cyclic task to identify three representative work cycles and determine task duration (s) for each representative work cycle.

2.2.3. Current Study Data Collection: Strain Index

2.2.3.1. Categorizing Tasks into Homogenous Exposure Groups

Because many participants performed the same task, efforts to conduct SI ratings among the 886 tasks performed by study participants (individual tasks) would have been redundant and were not feasible due to limited resources. Prior to data extraction for the current study, individual tasks that were similar were assigned to a task group (task similarity groups). Individual tasks characterized by the same SI intensity of exertion rating and approximately the same function were classified as similar for our study. A more detailed description of the procedures used to establish and verify task similarity groups is presented in Appendix B. Among the 886 tasks, 162 unique, solitary tasks and 179 task groups were identified for a total of 351 task-specific SI ratings to be conducted (Table 2.4.).

2.2.3.2. Selecting Video Segments Used for SI ratings

For the current study, 351 task-specific SI ratings were ascertained. For efficiency, for each task group, SI task parameter rating estimates were ascertained for one, randomly selected, individual task. For each cyclic task, at least one minute of video and at least one complete representative work cycle were selected and used to ascertain SI ratings. In general, among the three representative work cycles identified for the Iowa Study, Cycle 2 was the default cycle selected for rating for the current study. If the default criteria were not met (*e.g.* Cycle 2 duration was less than one minute), then alternate criteria were used to select a different cycle or combination of cycles. A more detailed description of cycle selection procedures is presented in Appendix C.

2.2.3.3. Identifying Forceful Exertions

Five of the six SI task parameter rating criteria are contingent on trained observers accurately identifying, ascertaining the duration of, and characterizing the intensity of forceful exertions. The following definitions were established as guidelines for the current study. First, an exertion was defined as a required hand/wrist motion that involves hand or forearm muscular effort during task performance, regardless of the force required (S. Bao, Howard et al., 2006; Fallentin et al., 2001; Konz & Johnson, 2004). For this study, a *forceful exertion* was defined as a required, work-related hand/wrist motion, or action (*e.g.* using the hand to hold, manipulate, trigger, push, pull, or otherwise handle an object) that was estimated to require a non-negligible level of force (≥ 8.9 N) (S. Bao, Howard, Spielholz, Silverstein, & Polissar, 2009; Stetson, *et al.*, 1991; Kapellusch & Garg, personal communication, May 12, 2008). For the current study, trained observers estimated whether the hand force for an exertion was at least 8.9N. The 8.9N value was selected based on the value used by Bao *et al.* (2009). A detailed flow chart for the rules used to identify forceful exertions is presented in Figure 2.1.

2.2.3.4. Estimating Strain Index Task Parameter Rating Criterion

2.2.3.4.1. Consensus Approach

As recommended in the literature, for this study the two raters viewed the video recordings independently and used the methods described below to select initial rating criterion categories for the following SI task parameters (Table 2.1.): intensity of exertion, hand-wrist posture, speed of work, percent duration of exertion, and efforts per minute. Afterwards, a consensus approach was used to select a final SI task parameter rating criterion category for each of the five SI task parameters mentioned above. When the raters' initial rating criterion categories (and multiplier values) were not identical, then the raters met, watched the video segments, and agreed upon a final rating criterion category.

2.2.3.4.2. Qualitative Methods

Qualitative methods were used to select a rating criterion category for the intensity of exertion, hand-wrist posture, and speed of work SI task parameters. To ascertain the intensity of exertion rating criterion, raters watched the video segments(s) for each task several times. The specific intensity of exertion rating criterion category (Light, Somewhat Hard, Hard, Very Hard, or Near Maximal) selected for a task was chosen based on the hand force observed during the most intense forceful exertion. All intensity of exertion ratings were made assuming that the hand activity was performed with a neutral posture by a healthy adult. Because the SI was developed to rate job tasks rather than workers, intensity of exertion ratings were made relative to maximal strength among the general population of manufacturing workers, not the particular worker observed in the video segment.

For the current study, raters referred to a 0-10 visual analog scale (Figure 2.2) when selecting an intensity of exertion rating criterion category (Table 2.1.). This visual analog scale (Figure 2.2) was created for the current study that combined elements of the SI user's guide (Moore & Garg, 1995), the Hand Activity Level scale for rating peak hand force (American Conference of Governmental Industrial Hygienists (ACGIH), 2001; Latko et al., 1997) and four additional verbal anchors (very little force, mild force, moderate force, and high force). The four additional verbal anchors were added to clarify the verbal anchors included in the SI user guide. When the approximate weight of a particular tool or object could not be estimated, then raters discussed the task with research assistants who had collected video and physical exposure data for the Iowa Study.

The qualitative method used to select a hand-wrist posture rating criterion category (Very Good, Good, Fair, Bad, Very Bad) was similar to the method used for intensity of exertion. However, estimations for hand-wrist posture were based on the most common (longest duration) wrist posture used during forceful exertions. Trained observers watched the video segments and, using the verbal descriptors and the wrist extension, flexion, and ulnar deviation angles presented in Table 2.2., selected a hand-wrist posture rating criterion category to characterize the most common wrist posture used during the task. Similarly, raters used the verbal descriptors for speed of work presented in Table 2.2 to select the speed of work rating criterion category that most accurately described the overall work pace of study participants.

2.2.3.4.3. Quantitative Methods

Quantitative methods were used to ascertain rating criterion for the duration per day, percent duration of exertion and efforts per minute SI task parameters. Information on daily hours worked per task per shift was collected from participants' daily diaries and used as the basis for selecting a rating criterion category for the duration per day SI task parameter. To ascertain task-specific values for percent duration of exertion and efforts per minute, trained observers conducted detailed, frame-by-frame video observations (time-studies) of a worker performing the task. Specifically, while an observer viewed video clip(s) for a task, all forceful exertions were identified. Then, each forceful exertion was viewed in slow motion and precise video start and the stop times were documented. For consistency across raters, rules were developed to clearly define when a forceful exertion started and ended (Figure 2.3). Detailed flow charts for the rules used to determine the duration for each forceful exertion are presented in Figures 2.1 and 2.3. The general rule was that a forceful exertion ended when observers noticed a change in the intensity or direction of the principal hand force.

After conducting a time study, a task's percent duration of exertion was calculated by dividing the total duration of all forceful exertions (s) by the duration of the observed video segment(s). Efforts per minute were calculated by dividing the number of forceful exertions counted by the duration of the observed video segments (min). Using the cut-points presented in Table 2.1., the calculated values for percent duration of exertion and efforts per minute were categorized to select percent duration of exertion and efforts per minute SI task parameter rating criterion categories and multiplier values.

2.2.3.4.4. Modified Methods for Non-Cyclic Tasks

Traditionally, the SI has only been used to evaluate cyclic tasks. A cyclic task is composed of a set of work elements repeated over the course of a task. However, 19% (N = 54) of participants in the Iowa Study performed at least one non-cyclic task. To maximize sample size, modified SI procedures were developed for rating non-cyclic tasks.

The SI methods used to select the rating criterion category for intensity of exertion, hand-wrist posture, and speed of work for non-cyclic tasks were similar to the established methods described above. However, the method for selecting video segments to observe for cyclic tasks was not applicable to non-cyclic tasks. Detailed time-studies of forceful exertions were not conducted for non-cyclic tasks. Instead, less detailed time-studies were conducted to identify the most common work element. A work element is a functional part of a task that is associated with one or more exertions (*e.g.* remove the clear film protective coating from a stainless steel refrigerator door, move a door from the conveyor and put it on a rack, plug the holes in a refrigerator liner, attach a skid to the basepan, etc.). The most common work element was defined as the work element with the longest total duration. After the most common work element was identified, intensity of exertion, hand-wrist posture, and speed of work rating criterion categories were selected as described above. Mean values for percent duration of exertion and efforts per minute by work area (*e.g.* crating, brazing) were assigned to non-cyclic tasks in the same work area unless the estimates were unstable (wide 95% CI). When the lower and upper bound 95% CI values did not correspond with the same rating criterion category (*e.g.* lowest duration of exertion rating criterion category = < 10%, Table 2.1.) then estimates were considered unstable and facility-wide values were assigned.

<u>2.2.3.4.5. Imputing SI Exposure Data</u>

It was not possible for the Iowa Study research team to collect video data for all tasks. The percent of missing task exposure data was relatively small (5% of total task hours) but at some point during the study, 32% (N = 89) of the participants performed a task for which exposure data had to be imputed. Therefore, to maximize statistical power we developed imputation methods for the SI, otherwise our sample size would have been 187 instead of 276.

Strain Index task parameter multiplier values were imputed when video recordings were not available. The imputation procedures established for the Iowa Study were used as guidelines for the current study. Mean values for percent duration and efforts per minute by dominant hand were pooled by department and across all departments (facility-wide). The pooled department values were used to assigned percent duration and efforts per minute SI task parameter multiplier values to tasks with missing data in the same department unless the estimates were unstable (wide 95% CI – see previous section). In that case the facility-wide values were assigned. For intensity of exertion, hand-wrist posture, and speed of work SI task parameters, the multiplier values for tasks that were videotaped were pooled by department and across all departments (facility-wide), and the pooled values were assigned as SI task parameter multiplier values for tasks with missing values. All task' exposure measures that were imputed using facility-wide means for the Iowa Study were assigned facility-wide pooled SI task parameter multiplier values for the current study. Also, pooled SI task parameter multiplier values by department were typically used if the Iowa Study had used the participant's personal average across all other tasks performed.

2.2.3.5. Calculating SI Scores

In the literature, formulas used to calculate SI scores for multi-task jobs vary between investigators; however there seems to be agreement on the following principles and assumptions for calculating SI scores for multi-task jobs (Stephen Bao et al., 2009; Garg, 2006):

1. The multi-task job SI score should be greater than or equal to the highest SI score among all tasks performed.

2. For each additional task performed in a multi-task job, an "incremental increase" in exposure to biomechanical risk factors is produced.
3. The incremental increase in exposure associated with each additional task performed is dependent on the magnitude of the SI task parameter ratings for additional tasks performed.
4. The incremental increase in exposure associated with each additional task performed is independent of exposure measures for preceding tasks.

In general terms, for the current study all SI scores were calculated by taking the sum of 1) the highest SI score among all tasks performed per shift, and 2) the incremental increases in exposure for each additional task, as estimated by the SI. A detailed description of the formulas and procedures used to calculate SI scores with the CSI computation method is presented in Appendix D.

2.2.3.6. Assigning SI Risk Categories

The Original and Empirical SI classification methods were used to create the two time-varying exposure variables of interest for this study - Original and Empirical SI risk category. Both methods categorized the peak daily SI scores for each work week (Monday – Sunday) per participant. The Original Structure used the three original cut-points presented by Moore and Garg (1995) to assign four Original SI risk categories: Category $1_{Original}$ (SI score ≤ 3), Category $2_{Original}$ (SI score > 3 and < 5), Category $3_{Original}$ (SI score ≥ 5 and < 7), and Category $4_{Original}$ (SI score ≥ 7).

In contrast, empirical methods developed for this study were used to select the three cut-points for an Empirical Structure. The four Empirical SI risk categories were assigned based on the following ranges of SI scores: Category $1_{Empirical}$ (SI score ≤ 8.72), Category $2_{Empirical}$ (SI score > 8.72 and < 13.5), Category $3_{Empirical}$ (SI score ≥ 13.5 and < 18.56), and Category $4_{Empirical}$ (SI score ≥ 18.56). The empirically derived cut-points (8.72, 13.5, and 18.56) chosen for the Empirical Structure were based on SI score quartiles among the 97 symptom-positive (Sx+) participants for the peak daily SI Score during the week of the event. In this way, approximately equal numbers of incident Sx+ events were distributed across the four Empirical SI risk categories. This strategy was chosen because estimates of relative risk can be more precise and less subject to instability caused by sparse numbers of symptom event weeks in a particular SI risk category.

2.2.3.7. SI terminology

The SI jargon in the SI literature has not been used consistently by all authors. In this dissertation whenever possible we chose terminology that is consistent with a recent publication by Bao *et al.* (2009). To assist readers, SI terminology used throughout this dissertation is summarized in Table 2.5. As previously mentioned, other, more general terminology used to describe work is summarized in Appendix A.

2.2.4. Statistical Analyses

2.2.4.1. Power Analysis

Prior to data extraction, a power analysis was performed using conservative assumptions of an incidence rate of 22.5 per 100 person years among participants in the lowest Empirical SI job risk exposure category (lowest quartile) and an odds ratio of 2.0 when compared to the highest Empirical SI risk category. Based on these assumptions, a sample size of 270 was needed for the proposed study to have 80% power (Lenth, 2006-9).

2.2.4.2. Descriptive Statistics

Means and standard deviations or frequency distributions for participant-specific time independent demographic, personal, and psychosocial/work organization covariates were calculated for all participants (N = 276) and stratified by gender. Similarly, descriptive statistics for weekly SI score, Original SI risk category, Empirical SI risk category and time-varying work organization covariates (*e.g.* weekly job stress, weekly job change, hours worked per week) were conducted for all participant weeks (N = 8826) and stratified by gender.

2.2.4.3. Crude Associations with Hand-Arm Symptoms

Separate unadjusted survival analyses were performed for the full sample and stratified by gender to estimate hazard ratios (HRs) and 95% confident intervals (CIs) for the association between incident hand-arm symptoms and 1) relevant covariates (demographic, personal, and psychosocial/work organization) and 2) each SI classification method (*i.e.* Original, Empirical). The proportional hazards assumption was tested for all time independent covariates.

The two independent SI exposure variables to be compared in this study, Original SI risk category and Empirical SI risk category, were time-varying, ordinal, categorical variables with four levels (Category 1 – Category 4). For the current study, relative risk (i.e., relative hazard) was calculated using survival analysis methods and instantaneous risk (*i.e.* incidence rate) was also calculated (Cox & Oakes, 1984; Kalbfleisch & Prentice, 1980). Survival time was taken as time from enrollment to outcome. Participants who were symptom free were censored at the time they left the study. Weeks to hand-arm symptom outcome was used as the dependent variable for unadjusted and multivariable analyses. Extended Cox models (Cox & Oakes, 1984) were used to accommodate time-varying independent variables. These methods allowed individuals whose weekly SI risk category varied during the course of the study to contribute person-time to more than one SI risk category (Kleinbaum & Klein, 2005). Dummy variables were created for Original and Empirical SI risk category metrics. Category 1_{Original} or Category $1_{\text{Empirical}}$ was used as the referent category.

2.2.4.4. Covariate Selection for Multivariable Models

Because of the relatively large number of covariates available, screening of covariates was performed with the goal of including only those that either 1) were actual confounders of the association between an SI risk category and incident symptoms or 2) explained substantial variability in the data. Specifically, demographic, personal, and psychosocial/work organization covariates associated with hand-arm symptoms with a probability of < 0.2 were identified and included with each SI risk category variable in a full multivariable model. Potential confounding variables were removed sequentially from the full model, starting with the least statistically significant covariate. All covariates were subject to removal. A covariate was retained in the final multivariable model if its removal resulted in either 1) a change of 15% or greater in the HR of any of the risk categories (Kleinbaum & Klein, 2005) or 2) a poorer fitting model. The Akaike Information Criterion (AIC) value (Akaike, 1973) was used to ascertain adequacy of fit for statistical models. Lower AIC values indicated a better-fitting model.

2.2.4.5. Multivariable Survival Analyses

The final multivariable models were then used for two multivariable analyses to estimate the association between time to development of hand-arm symptoms and two biomechanical exposures metrics: Original SI risk category and Empirical SI risk category.

2.2.4.5.1. SI Classification Method Comparison

The specific aim of this study was to compare models examining the association between Original SI risk category and incident hand-arm musculoskeletal symptoms to models examining the association between Empirical SI risk category and incident hand-arm musculoskeletal symptoms.

To address the specific aim of the current study, the multivariable Original and Empirical SI risk category models were compared using two criteria. First, models were compared for adequacy of fit using the absolute difference in AIC between the two models (Akaike, 1973). Second, linear hypothesis tests were conducted to test the null hypothesis that the parameter estimates for Original or Empirical SI Categories 2, 3, and 4 were not dissimilar. A lower *p*-value for the linear hypothesis test indicated that it was less likely that observed differences in parameter estimates for Category 2, 3, or 4 compared to Category 1 were due to chance alone.

2.2.4.5.2. *Post hoc* Models

After conducting the *a priori* multivariable analyses for Specific Aim 1, deficiencies were apparent for both the Original and the Empirical Structures. Namely, some useful information was lost about the association between SI Scores and incident hand-arm symptoms for both structures. Consequently, the investigators conducted analyses to develop a *post hoc* Structure to be tested among other populations in the future. The first step toward creating the *post hoc* Structure was to create a nine category SI classification method with approximately 10 Sx+ event weeks per category. Unadjusted analyses were conducted using the lowest risk category as the referent category. Linear hypothesis tests were conducted to test whether parameter estimates for adjacent categories were statistically dissimilar (Hosmer & Lemeshow, 1999). Adjacent categories that were not statistically dissimilar ($p > .20$) were collapsed to create a revised *post hoc* Structure. Multivariable survival analyses were conducted for the final *post hoc* SI risk category model using the same covariates used in the *a priori* multivariable survival analyses. Then the *post hoc* SI risk category model was compared to the two *a priori* SI risk category models using the same criteria described above. Specifically, the AIC was used to evaluate model fit for the *post hoc* SI risk category model compared to the two *a priori* models. Also, linear hypothesis tests were conducted to test whether the regression coefficients for all SI risk categories in the *post hoc* model were not dissimilar. The *p*-value results from linear hypothesis tests conducted on the three multivariable models (Original, Empirical, and *post hoc*) were compared to identify the most ideal set of cut-point values for this sample.

2.2.4.5.3. Models Excluding Jobs That Include Imputed Data or Non-Cyclic Work

Multivariable analyses conducted on the full study sample were compared to analyses conducted on samples that excluded 1) participants who performed any non-cyclic tasks or 2) participants who performed any tasks with imputed SI scores. The purpose of conducting these additional analyses was to examine whether observed associations between weekly SI risk category and hand-arm symptoms were substantially influenced by participants who performed at least one non-cyclic task or at least one task with imputed SI scores. Due to insufficient (< 5) numbers of Sx+ participant event weeks for some Original and *post hoc* SI risk categories, it was only possible to conduct multivariable analyses for the Empirical SI risk category model, and not for the Original or *post hoc* SI risk category models. These multivariable models included the same covariates used for the *a priori* and *post hoc* multivariable models.

2.2.4.5.4. Gender interaction

Multivariable analyses of the association between incident hand-arm symptoms and SI risk category stratified by gender were conducted for the Empirical Structure, but were not conducted for the Original or *post hoc* Structures, due to sparse (< 5) numbers of Sx+ participant weeks for some SI risk categories. Interaction was observed between hand-arm symptoms, gender and several covariates. Therefore, the same covariate selection procedures outlined above (Section 2.2.4.4.) were used to build separate multivariable models using the Empirical Structure for male and female participants.

All analyses were performed using SAS® version 9.2.

2.3. Results

2.3.1. Study Sample

Time independent and time-varying demographic, personal health and occupational characteristics for participants (N = 276) in the current study are presented in Table 2.3. Six of the 282 Iowa Study participants who were symptom negative at entry were excluded from the current study because their job task(s) could not be evaluated with the SI (i.e., cycle times of greater than six min). The mean age of participants was about 43 yr (SD = 10.0 yr), 48% were female, and the average length of employment at the facility was 16.3 yr (SD = 11.2 yr). The incidence of hand-arm symptoms was 57 per 100 person/years.

The participation rate was 52%. Some information was collected from non-participants. Compared to participants, the mean age of non-participants was 2 years younger, the mean number of years worked at the facility was about 4 years less for non-participants and a greater proportion were men (61% vs. 49%) who worked on second shift (50% vs. 32%).

2.3.2. Descriptive Task Data

Excluding imputed SI task parameter ratings, 351 distinct tasks were observed among the 1020 tasks performed by the 276 participants (Table 2.4.). The average cycle duration among all cyclic tasks was 62 s (SD = 26 s). A frequency histogram and cumulative percentage plot for weekly (Number of weeks = 8826) SI scores are presented in Figure 2.4. For a few tasks from the Iowa Study, poor video quality (*e.g.* obstructed views while working in confined spaces) made it impossible to ascertain SI task parameter rating criterion. In these instances, imputed values were used as described above in section 2.2.3.4.5. Overall, SI task parameters imputed using department summary data accounted for 3% of task hours and those imputed using facility-wide data accounted for 2% of task hours.

2.3.3. Survival Analyses

2.3.3.1. Crude Associations with Hand-Arm Symptoms

2.3.3.1.1. Personal, Demographic, Psychosocial and Work Organization Characteristics

Unadjusted associations between hand-arm symptoms and demographic, personal, and psychosocial/work organization covariates are presented in Table 2.6. Based on these analyses, potential confounders ($p < .20$) were sex, height, co-morbidities, previous hand-arm symptoms, hours worked at second job, hours per week of non-work-related hand intensive activity, job strain quadrant, weekly job stress, and weekly job change. A three-fold, statistically significant increase in the relative risk (Hazard ratio (HR) = 2.99, $p < .001$) of developing hand-arm symptoms was observed among participants with a history of prior hand-arm symptoms compared to participants with no history of prior hand-arm symptoms. For psychosocial job strain variables a two- to three-fold, statistically significant increase in risk (HR 2.2 – 3.5, $p < .05$) was observed for participants classified as “high control, high demand,” “low control, low demand,” or “low control, high demand” compared to those classified as “high control, low demand.” Weekly job changes were associated with a four-fold, statistically significant ($p < .001$) increase in risk for developing hand-arm symptoms among participants.

Several different associations were observed for demographic, personal, and psychosocial/work organization covariates by gender (Table 2.6.). In the current study, the overall risk of developing hand-arm symptoms was 77% higher for women compared to men ($p < .01$). Among men, although the associations were not statistically significant, age (HR = 0.98, $p = .13$) and years at facility (HR = 0.98, $p = .13$) were somewhat protective factors. Compared to female participants, men had lower crude associations between hand-arm symptoms and several demographic factors and higher crude associations between hand-arm symptoms and several psychosocial factors. For example, job demands, coworker support, and negative affectivity were identified as potential confounders (*p*-value < 0.2) among male participants, but not among female participants. Conversely, hand co-morbidities, ethnicity, education, hours/week at second job, supervisor support, BMI, and height were identified as potential confounders (*p*-value < 0.2) among female participants, but not among male participants.

2.3.3.1.2. SI Risk Category

Unadjusted associations between SI risk category and incident hand-arm symptoms and frequency distribution of participants' weekly Original and Empirical SI risk category by hand-arm symptom status are presented in Table 2.7. It was not possible to create an even distribution of Sx+ weeks among the four Empirical SI job risk categories due to clusters of Sx+ weeks among SI scores. Inspection of the results suggests that the Original Structure cut-points more clearly discriminate between symptoms positive and symptom negative participant weeks. Specifically, symptom negative participant weeks were overrepresented in Original Structure Category 1 (Category 1_{Original}) strata and were underrepresented in Original Structure Category 4 (Category 4_{Original}) strata to a greater degree than is observed among the analogous Empirical Structure strata. The observations just described were not analyzed with a statistical test because they were part of our unadjusted analyses.

None of the unadjusted associations between hand-arm symptoms and jobs assigned to Category 2_{Original} and Category 3_{Original} (SI scores > 3 and < 7) approached statistical significance (*p* > .5), but a monotonic increase in the HR was observed across Category 2_{Original}, Category 3_{Original} and Category 4_{Original} compared to Category 1_{Original} (Category 2_{Original}, HR = 1.19; Category 3_{Original}, HR = 1.39; Category 4_{Original}, HR = 1.80). For jobs in Category 4_{Original}, the 80% increase in risk observed compared to job with

Category $1_{Original}$ approached statistical significance (*p* =.07). For the Empirical Structure job risk categories, a 70% increase in relative risk (*i.e.* HR) was observed for Category $2_{Empirical}$ (*p* =.08) or Category $3_{Empirical}$ (*p* =.05) compared to Category $1_{Empirical}$. However, for Category $4_{Empirical}$, the magnitude of the HR was lower but not statistically significant (HR = 1.22, *p* = .48). Unadjusted models examining associations between the Empirical Structure and incident hand-arm symptoms had lower AIC (better fit) than models examining associations between Original Structure (AIC difference = 6.61) and incident hand-arm symptoms.

2.3.3.2. Multivariable Models

2.3.3.2.1. SI Classification Method Comparison

Final multivariable models of associations between the SI risk category and incident hand-arm symptoms were adjusted for sex, previous hand-arm symptoms, hours worked at second job, hours per week of non-work-related intensive hand activity, weekly job stress, and weekly job change (Table 2.8.). The absolute difference in AIC was 1.42, which may be considered a substantial difference in support of the model with the lower AIC value (Burnham & Anderson, 1998). In other words, substantial empirical evidence supports the use of the alternate Empirical SI cut-points compared to the Original SI cut-points. The strength of evidence provided by the AIC in support of the Empirical Structure is consistent with the lower *p*-value observed for the linear hypothesis tests (Empirical Structure, *p* = .05; Original Structure, *p* = .14).

Additionally, larger and statistically significant HRs were observed when multivariable models for both the Original and Empirical Structures were compared to their respective unadjusted models. For example, when Category $4_{Original}$ was compared to Category $1_{Original}$, the crude HR was 1.80 and not statistically significant (95% CI = 0.96-3.40); whereas a two-fold, statistically significant increase in the risk of developing hand-arm symptoms was observed (HR = 2.06, 95% CI =1.08-3.92) in the multivariable model

(Tables 2.7 and 2.8.). Similarly, when Category $3_{Empirical}$ was compared to Category $1_{Empirical}$, the crude HR of 1.70 was not statistically significant (95% CI = 0.99-2.91), whereas a more than a two-fold, statistically significant (HR = 2.21, 95% CI = 1.26-3.85) relative risk for hand-arm symptoms was observed in the multivariable model. As with the unadjusted models, the magnitude of increased risk was lowest for the highest Empirical risk category and the association was not statistically significant ($p = .23$).

2.3.3.2.2. *Post hoc* Model

Exploratory, *post hoc* analyses were conducted to develop a data-driven model for testing in future studies among other study populations. To better observe the shape of the dose-response relationship between SI score and incident symptoms, hazard ratios for each of nine equally spaced SI categories (each category with approximately 10 Sx+ weeks per category), with Category 1 as the referent group, were plotted. Linear hypothesis tests were conducted to test whether the parameter estimates for adjacent categories with similar HRs were statistically similar (Hosmer & Lemeshow, 1999). The parameter estimates were not statistically dissimilar for Categories 2 and 3 ($p = .76$), and Categories 5 through 8 ($p = .34$) (Figure 2.5.). Consequently, those categories were pooled and a five category *post hoc* Structure was created (Table 2.9).

The *Post hoc* multivariable model of association between hand-arm symptoms and the *post hoc* Structure is presented in Table 2.9. The same covariates included in the final multivariable models examining Original and Empirical Structures were also used in the multivariable models of the *post hoc* Structure. Based on the size of the *p*-value for this *post hoc* model linear hypothesis test, it was unlikely that the observed differences in the parameter coefficients for Categories 2, 3, 4 and 5 were observed due to chance alone ($p < .01$). Using SI scores ≤ 3 (Category 1) as the reference category, the most substantial and statistically significant HRs were observed when SI scores ranged from 10.25 to < 13

(HR = 3.74, $p < .001$) and from 13 to 27 (HR = 2.37, $p = .01$). Consistent with the multivariable model for the Empirical Structure, a 31% increase in risk was observed for the highest *post hoc* category (SI scores > 27) compared to the referent category (HR = 1.31, $p = .58$). All model fit evidence supported the *post hoc* Structure. In particular, for the *post hoc* Structure compared to the Empirical Structure, the absolute difference between AIC values was 5.4, in favor of the *post hoc* Structure and compared to the Original Structure the AIC difference was 7.0 in favor of the *post hoc* Structure (Burnham & Anderson, 1998). The degree of evidence provided by the AIC in support of the *post hoc* Structure is consistent with the lower *p*-value observed for the linear hypothesis tests (*post hoc* Structure, $p < .01$; Empirical Structure, $p = .05$, Original Structure, $p = .14$).

2.3.3.2.3. Models Excluding Jobs That Included Imputed Data or Non-Cyclic Work

When participants (N= 56) who performed at least one non-cyclic task during the study were excluded, multivariable associations between Empirical SI risk category and hand-arm symptoms were attenuated compared to models that included all participants (N = 276) (data not shown). In contrast, when participants (N = 114) who performed one or more tasks with imputed SI scores were excluded, the magnitude of multivariable associations between Empirical SI risk category and hand-arm symptoms were somewhat higher when compared to analyses that included all participants (N = 162). For example, the HR for Category 3 in comparison to Category 1 was 22% higher when the analysis was restricted to participants without imputed SI scores (N = 162) when compared to the analogous analysis using the full sample (data not shown).

2.3.3.2.4. Gender Interaction

Hazard ratios for Empirical SI risk categories are presented separately for males and females in Figure 2.6. A multivariable model examining associations between

Empirical SI risk category and incident hand-arm symptoms among women (Category $2_{Empirical}$, HR = 2.11, *p* = .08; Category $3_{Empirical}$, HR= 2.65, *p* = .01; Category $4_{Empirical}$, HR = 2.06, *p* = .07) had higher HRs and stronger associations than a model examining associations between men Empirical SI risk category and incident symptoms among men (Category $2_{Empirical}$, HR = 1.73, *p* = .31; Category $3_{Empirical}$, HR = 2.04, *p* = .14; Category $4_{Empirical}$, HR = .68, *p* = .07) (Figure 2.6). Additionally, the probability that chance alone accounted for observed differences between the parameter estimates for Categories 2, 3, and 4 was less likely for the multivariable model among women (*p* = .04) compared to the multivariable model among men (*p* = .13).

2.4. Discussion

2.4.1. SI classification methods

2.4.1.1. Summary

The Empirical SI classification method appears to be a somewhat better predictor of incident hand-arm symptoms compared to the Original SI classification method, especially among women. However the evidence was not compelling for either method. The current study was the first prospective study to examine associations between SI or SI scores and incident hand-arm symptoms. Both the Original and Empirical SI risk category were associated with incident hand-arm symptoms, however, empirical evidence favored using the empirically derived cut-points developed for the Empirical Structure. Although the SI was developed to evaluate tasks and jobs rather than people, results from multivariable analyses stratified by gender indicated that Empirical SI risk category was more predictive among female participants. Exploratory *post hoc* analyses were conducted to address some deficiencies observed for both *a priori* models. As a consequence, a five category *post hoc* Structure that was more predictive of hand-arm symptoms was proposed. In the future, the *post hoc* Structure should be tested for association with musculoskeletal outcomes among other study populations.

2.4.1.2. Evidence

The current study was the first to validate that SI risk category is associated with hand-arm symptoms using a prospective study design and the information necessary to permit control of personal demographic, and psychosocial/work-organization confounders. It appears that while the Empirical SI risk category cut-points developed for this study were a substantial improvement compared to the Original SI cut-points, evidence from both SI classification methods provided useful findings.

2.4.1.2.1. Original Structure

Results from the current study provide some empirical evidence to support the Original "Hazardous" (Category 4_{Original}) SI risk category established by Moore and Garg (1995). A monotonic increase in risk was observed across the Original SI risk categories. The relative increase in risk across categories was only statistically significant for the highest Original SI risk category (SI score > 7) compared with the lowest category (SI score ≤ 3). Over 70% of weekly SI scores observed in the current study were 7 or higher and were therefore categorized as "Hazardous" using the Original SI cut-points. Thus, when using the original SI cut-points it was not possible to model associations between hand-arm symptoms and SI scores for 70% of the weekly exposure data from the current study.

2.4.1.2.2. Empirical Structure

In contrast, the Empirical SI cut-points were all higher than seven, so more precise measures of association could be modeled for the effect of SI risk category on hand-arm symptoms among two-thirds of the weekly exposure data. For this sample population, elevated risk levels were observed among the higher strata Empirical SI risk categories relative to the referent category (SI scores ≤ 8.72). But in contrast to the Original Structure, a monotonic increase was not observed across the Empirical SI risk categories. The only HR for the Empirical Structure that was statistically significant was a two-fold increase in risk for the second highest category. This two-fold increase was somewhat lower compared to HRs observed by Silverstein *et al.* (2006) in the aforementioned study of CTS among manufacturing and healthcare workers. Specifically, compared to the referent category, when SI scores were 13.5 to 18.56, the HR was 2.11 in the current study compared to a range of 2.2 – 2.4 for the Silverstein *et al.* results.

<u>2.4.1.2.3. Comparisons to the Literature</u>

Since this is the first study of its kind, comparisons with previous SI studies of single- or multi-tasks jobs are limited. Compared to single-task SI computation methods, the HR of 1.89 observed in the current study was substantially lower compared to an odds ratio (OR) of 114 reported for pooled results (Moore et al., 2006) from three previous ecologic studies (Knox & Moore, 2001; Moore & Garg, 1995; Moore et al., 2001). But, due to the ecologic and retrospective study designs it is not appropriate to make a direct comparison with the survival analysis results from the current study.

Compared to other studies that have also used multi-task computational methods, results from the current study are consistent with one article and one conference proceedings paper in which associations between multi-task SI metrics and some hand-arm musculoskeletal health outcomes were reported (Drinkaus, Bloswick, Sesek, Mann, & Bernard, 2005; B. Silverstein et al., 2006). In a conference proceedings paper, Silverstein *et al.* reported associations between log transformed SI scores and incident carpal tunnel syndrome (CTS) among a large (N = 670), prospective study of manufacturing and healthcare workers. Using survival analysis methods, Silverstein *et al.* (2006) observed a 35% increase (HR = 1.35) in risk of developing CTS per unit of log transformed SI score when controlling for age, gender, and BMI. Given this association, calculations were made to compare the results between Silverstein *et al.* (2006) and the current study. Specifically, in the current study, an 89% increase in risk was observed for SI scores of seven or higher, which is consistent a 78% increase calculated based on Silverstein's results.

Drinkaus *et al.* conducted a small (N = 28) ecologic, retrospective, pilot study among automotive workers using methods similar to the original SI paper (Drinkaus et al., 2005). The investigators developed and compared two different multi-task metrics based on the SI. Both Drinkhaus *et al.* (2005) and the current study observed statistically significant associations between hand-arm health outcomes and multi-task SI metrics. However, a direct comparison of results between the Drinkaus *et al.* study and the current study are not possible due to differences in SI score computation methods and study design. Specifically, although the theoretical basis for one of the metrics used by Drinkaus *et al.*, the CARD (Cumulative Assessment of Risk to the Distal Upper Extremity), was similar to the CSI computation method used in the current study, the low range of final CARD cut-point values (1.0, 1.1, and 2.8 were proposed) indicate that final values for the CARD metric were substantially lower than SI scores calculated for the current study.

2.4.2. Multi-Task SI computation Methods

Originally, the SI was developed for evaluation of mono-task jobs. Since then, investigators have presented modified forms of the SI for multi-task jobs (Stephen Bao et al., 2009; Drinkaus et al., 2005; Garg, 2006). These theoretical multi-task SI computation methods, such as the CSI, have been presented by other investigators in the absence of empirical epidemiologic evidence. The current study used the multi-task CSI computation method presented by Garg (2006), one of the developers of the SI (Moore & Garg, 1995) rather than one of several methods proposed by Bao *et al.* (Stephen Bao et al., 2009). Among the multi-task methods presented by Bao *et al.*, the "CSI" and "peak-calculated" methods were most similar to the CSI computation method used for the current study. For several reasons it would not be possible to use methods presented by Bao *et al.* given the SI data extraction procedures used for the current study. First, intensity of exertion, hand-wrist posture, and speed of work task parameter estimates were ascertained per task rather than as separate estimates for each forceful exertion. Secondly, the current study used different criteria for defining forceful exertions than those used by Bao *et al.*

2.4.3. Gender Effects

For this sample population, the association between Empirical SI risk category and hand-arm symptoms was modified by gender. Gender interactions between hand-arm symptoms and Empirical SI risk category were observed, especially for the highest strata. Specifically, compared to the referent category, the highest strata of SI scores was associated with an increase in risk that approached statistical significance among women but a highly non-statistically significant association was observed among men.

2.4.4. *Post hoc* Exploratory Analyses

In this sample, it appeared that a five category *post hoc* Structure was a better predictor of outcome than either of the four category *a priori* SI classification methods discussed above. However, because of the *a posteriori* method used to define these categories, the cut-points may not be generalizable to any other population. We do not recommend that practitioners use the *post hoc* risk category cut-points until they have been tested among other manufacturing populations.

2.4.5. Limitations

The findings of this study suggest that the SI may predict future hand-arm symptoms among workers performing single-task and multi-task manufacturing jobs similar to those performed by the study sample. However, about 90% of the intensity of exertion task ratings at this facility were rated “Light” or “Somewhat Hard.” Observed associations between hand-arm symptoms and the SI metrics may have been attenuated due to the limited range of exposure to forceful hand-arm work observed at this facility.

Only manufacturing workers were included in this study, therefore it is uncertain whether the Empirical SI risk category cut-points can be generalized to other industries. However, compared to the Original SI cut-points, using the higher Empirical SI cut-points presented in this study may reduce the number of jobs that are incorrectly categorized as hazardous.

Another limitation in the current study was sample size. Among epidemiologic studies of musculoskeletal symptoms and disorders, a sample size of 276 is not considered small. Regardless, statistical power in this study was limited due to sparseness within some strata of categorical variables. Estimates of association for the Original SI cut-points were unstable due to sparse numbers of Sx+ participants in Original SI risk Category 2 and Category 3. In addition, analyses by gender were especially limited by sample size considerations.

Additionally, we recognize that the participation rate of 52% may have resulted in sample distortion. It is possible that the associations between exposure and outcome among participants were different than among non-participants. However, the Iowa Study participation rate of 52% is consistent with the experience of many investigators conducting prospective cohort studies.

Furthermore, we do not believe that the difference in associations observed between the original SI category structure and hand-arm musculoskeletal symptoms and the empirical SI and hand-arm musculoskeletal symptoms was an artifact of participation. For this to occur, participation would have been related differentially to the association between the two SI categorization methods and MS symptoms. No plausible mechanism for such differential participation could be hypothesized.

One unexpected observation for the current study was that the lowest risk of developing hand-arm symptoms was observed for the highest strata of SI scores for the Empirical Structure. A possible explanation for the relatively lower HRs observed among the highest Empirical SI risk category could be a form of selection bias called selective survival. In other words, participants in this study had been working at the facility for many years (mean = 16 years); therefore, workers who were more susceptible to hand-arm symptoms may be underrepresented among this sample because they no longer worked at the facility.

2.4.6. Practical Applications and Future Research

Future research is needed to test the Empirical SI cut-points presented in this paper 1) when assessing single-task jobs, 2) when multi-task SI scores have been calculated using alternate methods, 3) among other populations of manufacturing workers, and 4) among workers in other industries. As previously mentioned, several multi-task SI calculation methods have been presented in the literature. These methods are all based upon the same underlying principles, but SI score values may vary by method.

In the current study it was not possible to estimate associations between hand-arm symptoms separately for participants with single-task and multi-task jobs. Theoretically, mean multi-taskSI scores should be slightly higher than mean single-task SI scores. Even so, when evaluating single-task SI scores it may be useful to substitute the cut-points from the Original Structure with the alternate cut-points from Empirical Structure introduced in this study.

In addition to future research, future software development could be another way to make the use of multi-task SI computation methods such as the CSI more accessible to practitioners. Until CSI calculation software becomes available, widespread use of the

CSI is unlikely because manual calculation of more than a few multi-task SI scores may be too time consuming.

The research presented in the current study addressed gaps in the literature regarding the SI risk category structure and the lack of methodologically rigorous epidemiologic evidence to support the use of the SI. Other gaps in the SI literature remain. Although some investigators are examining alternate SI task parameter multiplier values, at this point, no research has been published. Also, previous studies that have compared the SI to other exposure assessment methods have not used direct measures such as surface electromyography (EMG) for comparison and were not prospective in design.

The research presented in the next chapter of this dissertation, Strain Index Study II, will assess Empirical SI risk category as an exposure assessment method compared to separate estimates of exposure to force, repetition, and posture with a greater degree of accuracy. Lastly, the detailed time studies necessary for ascertaining some SI task parameters are tedious and time consuming. In the future, alternate methods of ascertaining rating criterion for intensity of exertion, hand-wrist posture, percent duration of exertion and efforts per minute by using direct measures such as surface electromyography or electrogoniometery should be explored.

2.5. Conclusion

The results of the current study will allow researchers and occupational health practitioners to better identify hazardous jobs and target those jobs for exposure reduction efforts. For the first time, this study provides empirical evidence of an association between SI risk category and incident hand-arm symptoms. Furthermore, if the results from this study are verified, then some evidence supports the use of alternate, empirically derived cut-points developed for the Empirical SI classification method compared to the cut-points originally recommended by Moore and Garg. However, until further research is conducted, we do not know whether the Empirical SI classification method will be associated with incident hand-arm symptoms among workers in other industries.

Table 2.1. Rating criterion category and multiplier values for the six SI task parameters. Rating criterion multiplier values are used to calculate a task's SI score.

SI task parameters			
Type	Name	Rating criterion	Multiplier values
Qualitative			
	Intensity of Exertion	Light	1.0
		Somewhat hard	3.0
		Hard	6.0
		Very hard	9.0
		Near maximal	13.0
	Hand/Wrist Posture	Very good	1.0
		Good	1.0
		Fair	1.5
		Bad	2.0
		Very bad	3.0
	Speed of Work	Very Slow	1.0
		Slow	1.0
		Fair/Normal speed	1.0
		Fast	1.5
		Very fast	2.0

Note: See Moore & Garg, 1995, for the complete user guide.

Table 2.1. continued

SI task parameters			
Type	Name	Rating criterion	Multiplier values
Quantitative: extracted from video observations of task			
	Duration of Exertion (% of cycle)	< 10	0.5
		10-29	1.0
		30-49	1.5
		50-79	2.0
		≥ 80	3.0
	Efforts per minute	< 4	0.5
		4-8	1.0
		9-14	1.5
		15-19	2.0
		≥ 20	3.0
Quantitative: extracted from daily task logs			
	Duration per day (h)	0-1	0.25
		1-2	0.50
		2-4	0.75
		4-8	1.00
		> 8	1.50

Note: See Moore & Garg, 1995, for the complete user guide.

Table 2.2. Verbal descriptors used when rating qualitative SI task parameters for "hand/wrist posture" and "speed of work"

Hand-wrist Posture					Speed of Work	
Rating criterion	Wrist Extension	Wrist Flexion	Ulnar Deviation	Perceived posture	Rating criterion	Perceived speed
Very good	0° - 10°	0° - 5°	0° - 10°	Perfectly neutral	Very Slow	Extremely relaxed pace
Good	11° – 25°	6° – 15°	11° – 15°	Near neutral	Slow	"Taking one's own time"
Fair	26° – 40°	16° – 30°	16° – 20°	Non-neutral	Fair/ Normal	"Normal" speed of motion
Bad	41° - 55°	31° - 50°	21° - 25°	Marked deviation	Fast	Rushed, but able to keep up
Very bad	> 60°	> 50°	> 25°	Near extreme	Very Fast	Rushed and/or barely unable to keep up

Note: See Moore & Garg, 1995, for the complete user guide.

Table 2.3. Descriptive statistics of time independent and time-varying demographic, personal health and occupational characteristics (N = 276)

Characteristic	Mean	(SD)	N	(%)
Time independent characteristics				
Age	42.8	(10.0)	--	
Female sex	--		133	(48.2)
Height males (cm)	179.2	(9.1)	--	
Height females (cm)	165.6	(6.6)	--	
BMI	27.4	(5.5)	--	
Education beyond High School	--		80	(29.0)
Proportion right handed	--		241	(87.3)
Non-white ethnicity	--		23	(8.3)
Annual Household Income >= $50,000	--		112	(40.6)
Hormone medication (% of women)	--		29	(10.5)
Currently smoke	--		94	(34.1)
Hand outcome comorbidity	--		38	(13.8)
Past history of hand-arm pain	--		50	(18.1)
Second shift	--		69	(25.0)
Years at study worksite	16.3	(11.2)	--	
Time-varying characteristics				
Hours per week at second job	1.2	(4.7)	--	
Hours per week UE intense activities	2.3	(3.8)	--	
Hours per week non-work aerobic activity	0.4	(0.9)	--	
Hours per week primary assembly job	36.9	(8.2)	--	

Table 2.4. Frequency of participants among task similarity groups. For each task similarity group, Strain Index ratings were conducted for one randomly sampled video clip and the ratings were assigned to all participants in the group.

Number of participants in group	N	(%)
1 (unique tasks)	162	(46%)
2	78	(22%)
3	43	(12%)
4	23	(7%)
5-9	37	(11%)
10-20	8	(2%)
Total task similarity codes	351	

Note: imputed task similarity groups excluded

Table 2.5. A summary and explanation of SI-specific terminology used in this dissertation.

Word or phrase	Explanation
Category $1_{\text{Empirical}}$	the lowest strata Empirical SI risk category; tasks/jobs with the lowest range of SI scores are assigned to Category 1; used as the referent category in survival analyses; the lower quartile of SI scores among symptom-positive event weeks for this study; SI score ≤ 8.72;
Category 1_{Original}	the lowest strata Original SI risk category; tasks/jobs with the lowest range of SI scores are assigned to Category 1; it is used as the referent category in survival analyses in this dissertation; in the original SI user guide the name for this category was “Safe”; SI score ≤ 3
Category $2_{\text{Empirical}}$	the second quartile of SI scores among symptom-positive event weeks for this study; SI score > 8.72 and < 13.5
Category 2_{Original}	in the original SI user guide the name for this category was “Uncertain”; SI score < 3 and < 5
Category $3_{\text{Empirical}}$	the third quartile of SI scores among symptom-positive event weeks for this study; SI score ≥ 13.5 and < 18.56
Category 3_{Original}	in the original SI user guide the name for this category was “Some Risk”; SI score ≥ 5 and < 7
Category $4_{\text{Empirical}}$	the highest strata Empirical SI risk category; the fourth quartile of SI scores among symptom-positive event weeks for this study; SI score ≥ 18.56;
Category 4_{Original}	the highest strata Original SI risk category; in the original SI user guide the name for this category was “Hazardous”; SI score ≥ 7
Cumulative Strain Index (CSI)	a specific SI computational method used to calculated SI scores for multi-task jobs; the CSI computational method was used to calculate all SI scores for this study (Garg, 2006)
Empirical SI classification method	the name of the SI classification method that assigns SI risk categories by applying a set of empirically derived cut-point values that were developed for this dissertation
Empirical SI risk category	an SI exposure metric with four ordinal categories; created by the Empirical SI classification method using the Empirical Structure of cut-point values
Empirical Structure	the set of three empirically derived cut-point values that were introduced in this dissertation and are used to ascertain Empirical SI risk categories
initial rating criterion category	when using a consensus approach, the initial rating criterion category is the pre-consensus rating criterion category selected by an SI rater for a particular SI task parameter
Original SI classification method	the SI classification method that uses the cut-points originally introduced by Moore & Garg to assign SI risk categories; a method of assigning SI risk categories by applying a set of cut-point values that were originally introduced by Moore & Garg to SI scores
Original SI risk category	an SI exposure metric with four ordinal categories; created by the Original SI classification method using the Original Structure of cut-point values
Original Structure	the set of three cut-point values that were originally introduced by Moore & Garg and are used to ascertain Original SI risk categories
post hoc SI classification method	the name of the SI classification method that assigns SI risk categories by applying a set of empirically derived, *post hoc* cut-point values that were developed for this dissertation

Table 2.5. continued

post hoc SI risk category	an SI exposure metric with five ordinal categories; created by the *post hoc* SI classification method using the *post hoc* Structure of cut-point values
post hoc Structure	the set of four empirically derived cut-point values that were introduced in this dissertation and are used to ascertain *post hoc* SI risk categories
preliminary SI score	the product of all SI task parameter multiplier values except duration per day
qualitative methods	a phrase used to describe the method of ascertaining rating criterion categories for the intensity of exertion, hand-wrist posture, and speed of work SI task parameters
quantitative methods	a phrase used to describe the method of ascertaining rating criterion categories for the percent duration, efforts per minute, and duration per day SI task parameters
SI classification method	a method of assigning an SI risk category to task or job by categorizing the SI score that was ascertained for the task or job
SI computation methods	any method used to compute a SI score
SI rater	a trained observer who conducts SI ratings
SI rating criterion	a rule used to estimate the magnitude of exposure for SI task parameters
SI rating criterion category	for each SI task parameter, an ordered list of five rating criterion categories have been established; for example, for the *intensity of exertion* task parameter, the five rating criterion are *Light, Somewhat Hard, Hard, Very Hard, and Near Maximal (Moore & Garg, 1995)*
SI rating(s)	1) the process of ascertaining an SI score for a task; 2) a general term to refer to SI exposure estimates for one or more SI task parameters
SI risk categories	a categorical SI exposure metric composed of several ordinal categories associated with a range of SI scores
SI score	the output of any SI computation method is referred to as an SI score; for the original, single-task SI method, the SI score was the product of the six SI task parameter multiplier values
SI task parameter multiplier value	an established unitless numerical value that has been assigned for each SI task parameter rating criterion category according to the SI users guide (Moore & Garg, 1995)
SI task parameters	when ascertaining an SI score for a specific task, trained observers (SI raters) rate the magnitude of workers' exposure to the following six *SI task parameters*: intensity of exertion , hand/wrist posture, speed of work, percent duration of exertion, efforts per minute, and duration per day
<*SI task parameter*> ratings	the process of selecting a rating criterion category for the a particular SI task parameter (*e.g.* intensity of exertion ratings)
Strain Index (SI)	a widely used observation-based exposure assessment technique that combines measures of important upper extremity biomechanical risk factors (upper extremity forceful exertion, repetition, and awkward hand/wrist postures) into a single scale (Moore & Garg, 1995)

Table 2.6. Unadjusted associations between hand-arm symptoms and potential demographic, personal, and psychosocial/work organization confounders by gender.

	Facility-wide (N = 276)		Male (N = 143)		Female (N = 133)	
Variable	Crude HR	*p*	Crude HR	*p*	Crude HR	*p*
Age (years)	0.99	0.57	0.98	0.13	1.00	0.93
Female sex	1.77	<0.01	--	--	--	--
Height						
Lower tertile	1.40	0.16	0.98	0.96	1.56	0.39
Middle tertile	1.00	-----	1.00	-----	1.00	-----
Upper tertile	0.84	0.50	0.54	0.11	0.69	0.74
BMI (units)	1.02	0.40	0.99	0.81	1.03	0.17
Education beyond HS	0.96	0.86	0.72	0.34	1.80	0.06
Right handed	0.97	0.91	0.82	0.65	1.05	0.90
Non-white ethnicity	0.84	0.65	0.68	0.47	3.18	0.05
Income >= $50,000	0.86	0.46	0.77	0.46	0.82	0.47
Current smoker	0.87	0.52	0.77	0.47	1.02	0.94
Co-morbidity (RA, DM, thyroid med, prior CTS)	1.80	0.02	0.70	0.63	1.82	0.03
Past history arm pain	2.99	<0.001	2.50	0.02	3.05	<0.001
Hours/week time in second job	1.05	<0.01	1.46	0.43	1.94	0.13
Hours/week UE intensive non-work activities	1.04	<0.01	1.04	<0.01	1.04	0.11
Non-work aerobic activity (none vs. some)	1.19	0.44	0.83	0.64	1.19	0.52
Second shift (versus first shift)	1.10	0.71	1.42	0.91	1.13	0.75
Years worked at the study facility	1.00	0.26	0.98	0.13	1.00	0.88
Hours worked each week	1.01	0.50	1.01	0.60	1.01	0.40

Table 2.6. continued

Psychosocial risk factor						
Coworker support	1.02	0.70	1.14	0.11	0.97	0.55
Supervisor support	0.96	0.27	1.03	0.67	0.94	0.15
Negative affectivity	1.02	0.25	1.05	0.12	1.00	0.99
Positive affectivity	0.98	0.27	0.98	0.44	0.99	0.42
Strain by "quadrant"						
"High control, low demand"	1.00	---	1.00	---	1.00	---
"High control, high demand"	2.61	<0.01	4.92	<0.01	1.66	0.24
"Low control, low demand"	2.22	0.02	3.81	0.03	1.49	0.35
"Low control, high demand"	3.50	<0.001	6.21	<0.01	2.10	0.05
Strain ratio (job demand/decision latitude)	11.69	<0.01	12.03	0.02	8.93	0.07
Decision latitude	0.98	0.01	0.97	0.07	0.98	0.17
Job demand	1.07	0.02	1.10	0.02	1.03	0.44
Stress (from task log VAS, time-varying)	1.17	<0.01	1.18	0.04	1.15	0.04
Job change (from task log, time-varying)	4.07	<0.001	4.76	<0.001	3.39	<0.001

Table 2.7. Unadjusted associations between SI risk category and hand-arm symptoms for the Original and Empirical Structures

SI risk category		weeks					
Classification method	Score range	Sx+	Sx—	HR	95% CI	*p*	AIC
Original Structure						0.27*	983.26
Category 1	≤ 3	11	1630	1.00	--	--	
Category 2	>3 and < 5	4	319	1.19	0.38-3.75	0.77	
Category 3	≥ 5 and < 7	6	619	1.39	0.51-3.77	0.52	
Category 4	≥ 7	76	6161	1.80	0.96-3.40	0.07	
Empirical Structure						0.17*	
Category 1	≤ 8.72	26	2907	1.00	--	--	976.65
Category 2	> 8.72 and < 13.5	18	1405	1.71	0.94-3.12	0.08	
Category 3	≥ 13.5 and ≤ 18.56	27	1849	1.70	0.99-2.91	0.05	
Category 4	> 18.56	26	2568	1.22	0.71-2.10	0.48	

Symptom positive = Sx+; symptom negative = Sx—; *Overall *p*-value is for the result of the linear hypothesis that $\beta_{Category2} = \beta_{Category3} = \beta_{Category4} = 0$

Table 2.8. Final multivariable models of association between SI risk category and hand-arm symptoms for the Original and Empirical Structures.

SI Risk category		weeks					
Classification method	Score range	Sx+/	Sx—	HR	95% CI	p	AIC
Original Structure						0.14*	883.32
Category 1	≤ 3	11	1630	1.00	--	--	
Category 2	>3 and < 5	4	319	1.25	0.39-4.01	0.71	
Category 3	≥ 5 and < 7	6	619	1.57	0.56-4.42	0.39	
Category 4	≥ 7	76	6161	2.06	1.08-3.92	0.03	
Empirical Structure						0.05*	881.753
Category 1	≤ 8.72	26	2907	1.00	--	--	
Category 2	> 8.72 and < 13.5	18	1405	1.57	0.83-2.96	0.18	
Category 3	≥ 13.5 and ≤ 18.56	27	1849	2.21	1.26-3.85	< .01	
Category 4	> 18.56	26	2568	1.42	0.80-2.50	0.23	

Symptom positive = Sx+; symptom negative = Sx—; *Overall *p*-value is for the result of the linear hypothesis that $\beta_{Category2} = \beta_{Category3} = \beta_{Category4} = 0$. Associations between Empirical SI risk category and hand-arm symptoms controlled for sex, non-work hand intensive activity, hrs at second job, weekly job change, previous hand-arm symptoms, and weekly job stress.

Table 2.9. *Post hoc* multivariable models of association between hand-arm symptoms and SI risk category for the *post hoc* Structure.

post hoc SI risk category	Score range	weeks Sx+/ Sx—		HR	95% CI	p	AIC
						< .01*	876.319
Category 1	≤ 3	11	1630	1.00	--	--	
Category 2	>3 and < 10.25	23	2438	1.40	0.67-2.92	0.55	
Category 3	≥ 10.25 and <13	10	242	3.74	1.54-9.12	< .001	
Category 4	≥ 13 and ≤ 27	44	2948	2.60	1.31-5.13	0.01	
Category 5	> 27	9	1471	1.31	0.53-3.19	0.58	

Symptom positive = Sx+; symptom negative = Sx—; *Overall *p*-value is for the result of the linear hypothesis that $\beta_{Category2} = \beta_{Category3} = \beta_{Category4} = 0$. Associations between Empirical SI risk category and hand-arm symptoms controlled for sex, non-work hand intensive activity, hrs at second job, weekly job change, previous hand-arm symptoms, and weekly job stress.

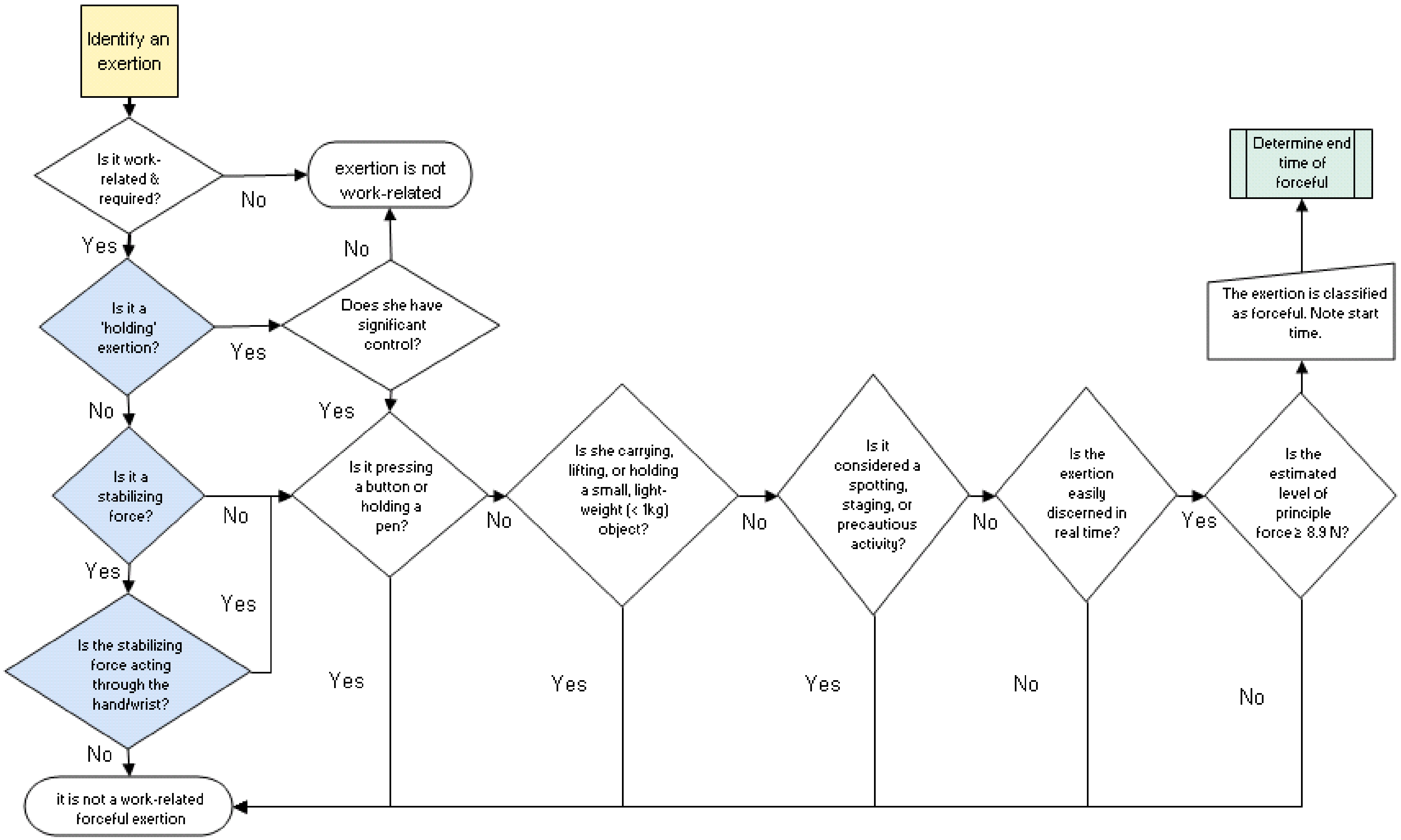
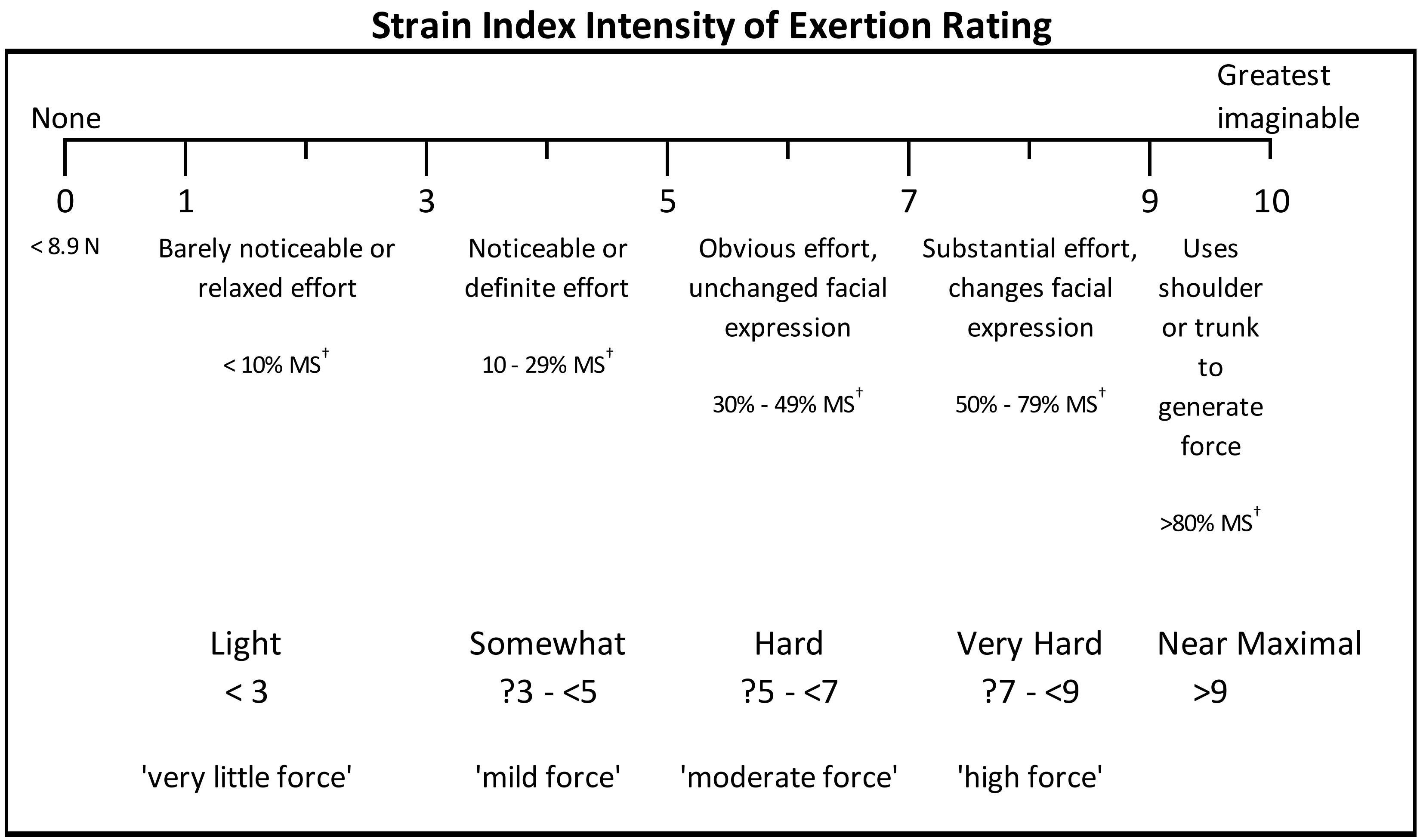


Figure 2.1. Flowchart for rules to identify forceful exertions



†MS = Maximal Strength (population based)

Figure 2.2. Visual-analog scale used when rating the "intensity of exertion" Strain Index task parameter

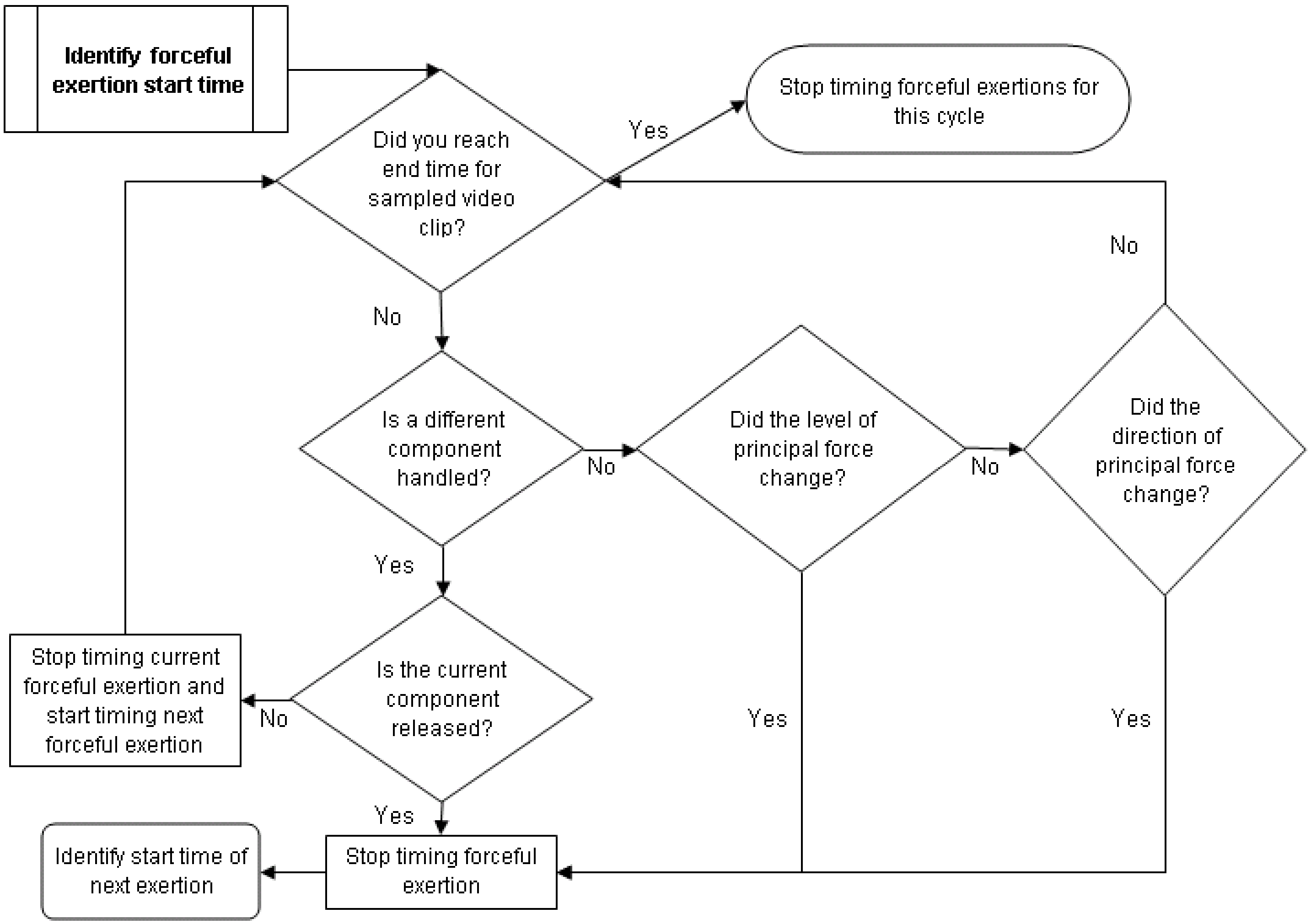


Figure 2.3. Flowchart for rules for determining the end time for a forceful exertion

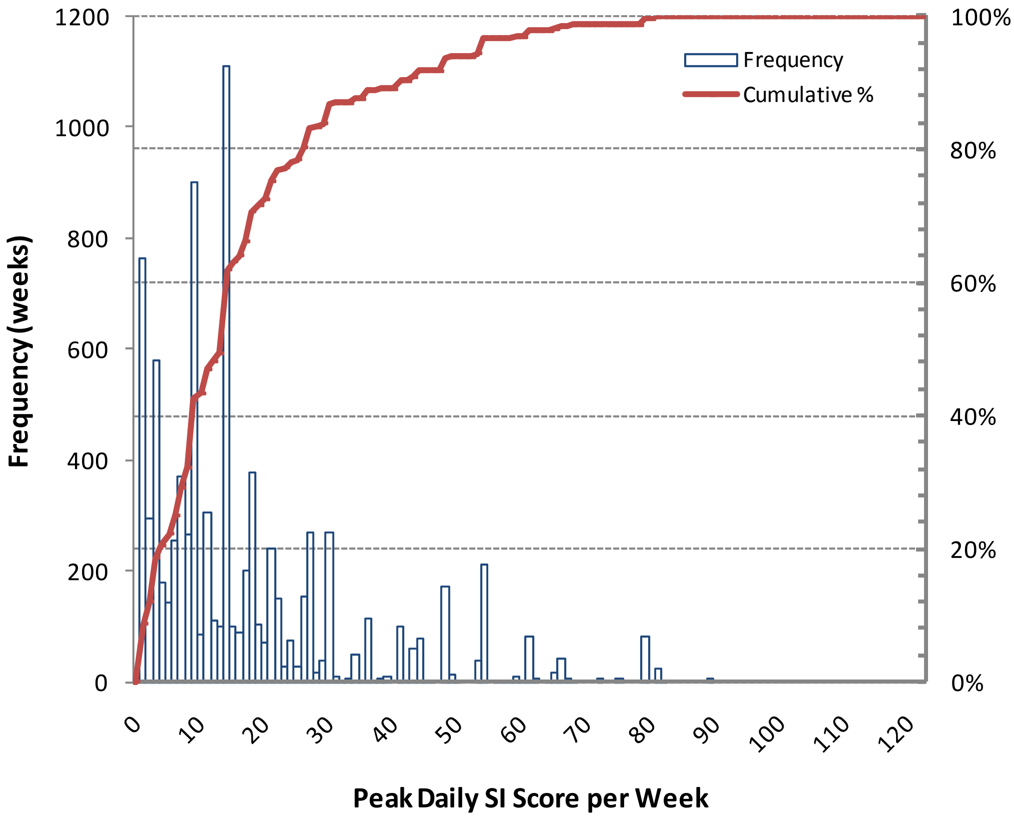


Figure 2.4. Frequency histograms and cumulative percentage plot for weekly (Number of participant weeks = 8826) SI scores.

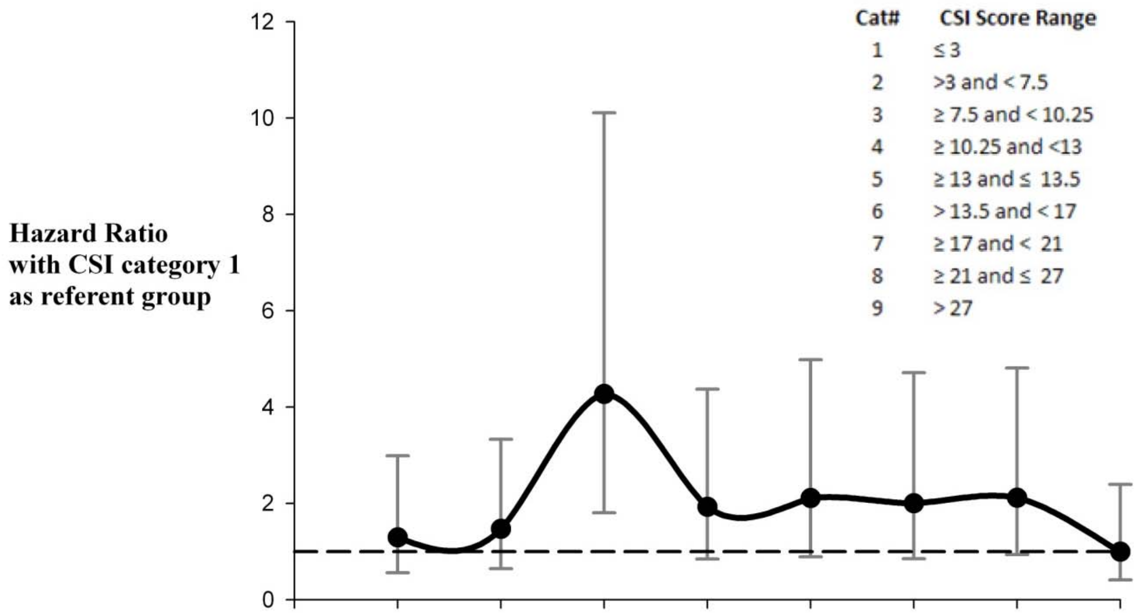


Figure 2.5. *Post hoc* analyses using cut-points to create nine SI risk categories with approximately ten or more events per category. Linear hypothesis tests were conducted to determine whether adjacent categories with similar hazard ratios were statistically similar. The parameter estimates were statistically similar for categories 2 and 3 (p = .76), and categories 5 through 8 (*p* = .34).

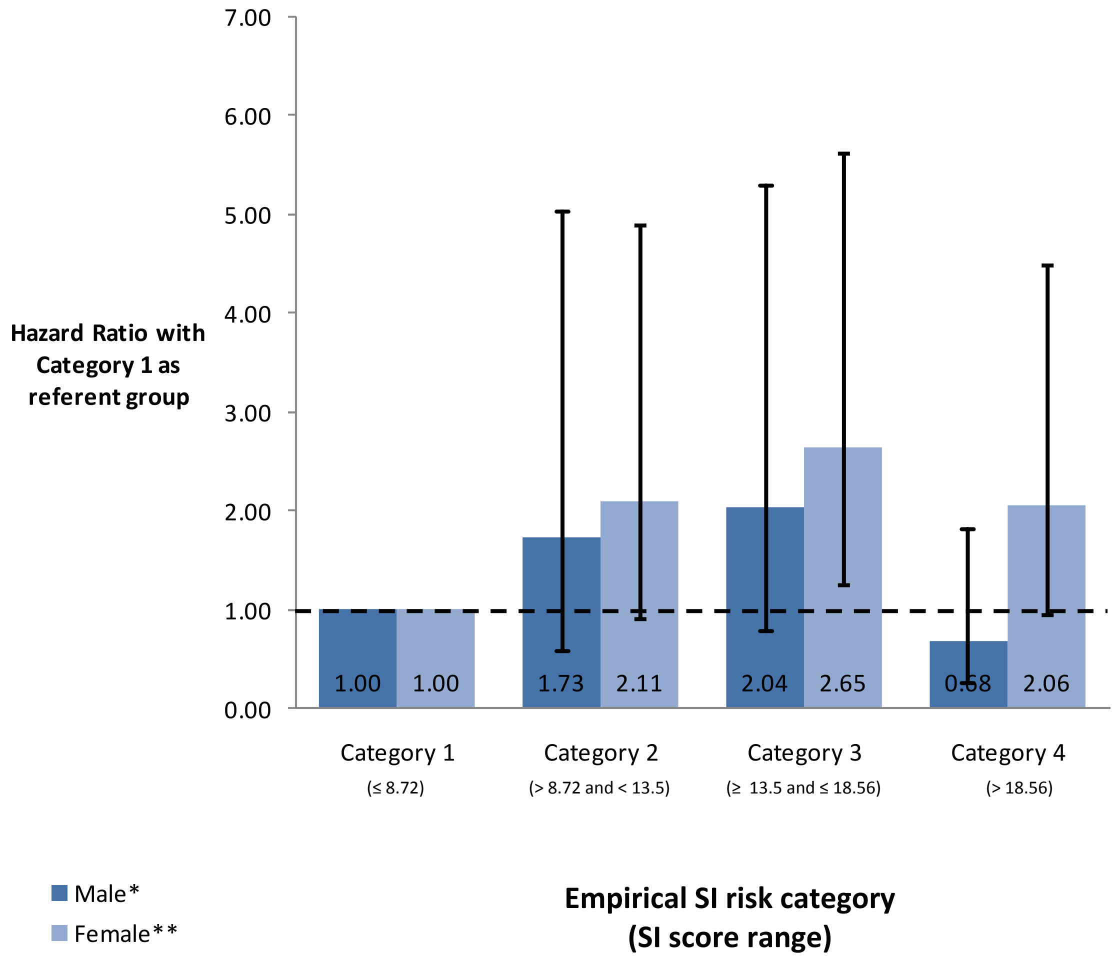


Figure 2.6. Bar chart of hazard ratios from gender stratified multivariable models of association between hand-arm symptoms and Empirical SI risk category. Error bars represent the upper limit of the 95% confidence interval.

*Associations between Empirical SI risk category and hand-arm symptoms for men were controlled for job strain quadrant, weekly job stress, weekly job change, and coworker support. The *p*-value = .13 for linear hypothesis test that $\beta_{Category2} = \beta_{Category3} = \beta_{Category4} = 0$.

**Associations between Empirical SI risk category and hand-arm symptoms for women were controlled for non-work hand intensity activity, weekly job stress, supervisor support, and previous hand-arm symptoms. The *p*-value = .04 for linear hypothesis test that $\beta_{Category2} = \beta_{Category3} = \beta_{Category4} = 0$.

CHAPTER 3. STRAIN INDEX STUDY II: EXPOSURE ESTIMATES AND ASSOCIATIONS WITH INCIDENT HAND-ARM SYMPTOMS FOR THE STRAIN INDEX COMPARED TO SEPARATE MEASURES OF FORCE, REPETITION AND NON-NEUTRAL WRIST POSTURE

3.1. Introduction

Forceful exertions, repetitive motions of the hand and wrist and non-neutral wrist postures have been identified as important biomechanical risk factors for upper extremity musculoskeletal disorders (UEMSDs) (Bernard, 1997). In the literature, a variety of exposure assessment methods have been used to quantify the amplitude, duration and frequency of exposure to forceful exertions, repetitive motions of the hand and wrist and non-neutral wrist postures. Laboratory and field-based research is available comparing the reliability, complexity and cost of specific exposure assessment methods. However, in the literature it is not common to find comparisons of exposure assessment methods by examining associations with prospective health outcome data. Conducting prospective studies can be impractical due to the costly and time consuming nature of the research. But empirical epidemiologic evidence of associations between incident UEMSDs or musculoskeletal symptoms and estimates of biomechanical exposures is useful (predictive validity). After all, when selecting a specific exposure assessment method, if the predictive validity of the method is poor, then reliability, accuracy, complexity and cost may be irrelevant. The following paragraph will discuss advantages and disadvantages of the three exposure assessment types (direct, observations, and self-report). Following that, a specific observation-based method, the Strain Index (SI), will be introduced because the study discussed in this chapter compared estimates of biomechanical exposure using the SI to several other biomechanical exposure assessment methods.

3.1.1. Measuring Exposure to Biomechanical Risk Factors

In order of decreasing degree of accuracy, complexity and cost, exposure assessment methods have been classified as direct, observational, or self-report (Winkel & Mathiassen, 1994). Direct methods produce quantitative exposure estimates but use sophisticated equipment, require greater expertise, are computationally intense, and can be impractical for use in field studies. Observational methods, on the other hand, are relatively unobtrusive and inexpensive which makes them especially practical for field-based research with large sample sizes. Observational methods do not require sophisticated equipment but do require more judgment on the part of the observer, and are vulnerable to observer bias compared to direct methods. There are a variety of self-reported methods (*e.g.* questionnaires) for exposure estimation of variable validity and usefulness. Virtually all self-report methods are inexpensive and, for exposures such as perceived exertion, may be the only method that provides an estimate of the domain to be measured. Besides tools that provide separate measures of force, repetition and non-neutral postures, a number of other methods, such as the Strain Index (SI), allow investigators to combine several risk factors into a single risk metric (Buchholz et al., 1996; Hignett & McAtamney, 2000; Karhu et al., 1981; McAtamney & Corlett, 1993; Moore & Garg, 1995; Occhipinti, 1998; Rodgers, 1992).

3.1.2. Review of Strain Index (SI) Procedures

The SI is a widely used observation-based exposure assessment technique that combines measures of forceful exertion, repetition, and non-neutral wrist postures into a single risk metric (Bernard, 1997; Dempsey et al., 2005; Jones & Kumar, 2006; Knox & Moore, 2001; Lee et al., 2005; Moore & Garg, 1995; Moore et al., 2001; Moore et al., 2006; National Research Council - Institute of Medicine, 2001; Rucker & Moore, 2002; Stephens et al., 2006; Stevens et al., 2004). To ascertain task-specific SI scores, trained observers first rate the magnitude of workers' exposure for six SI "task parameters":

intensity of exertion, hand/wrist posture, speed of work, percent duration of exertion, efforts per minute, and duration per day. To rate the magnitude of workers' exposure, the SI requires the observer to select the appropriate "rating criterion" category from a ordered list of categories established for each SI task parameter (Table 2.1.). For example, for the *intensity of exertion* task parameter, the five rating criterion are *Light*, *Somewhat Hard*, *Hard*, *Very Hard*, and *Near Maximal*.

SI procedures assign each rating criterion, for each SI task parameter, an established unitless numerical value (ranging from 0.25 to 13). In the peer-reviewed literature, these rating criterion values are referred to as SI task parameter "multipliers" (rating criterion values will be referred to as multipliers or multiplier values in this dissertation). The numerical multiplier values were established by Moore and Garg (1995) to account for the relative contribution of each rating criterion for each exposure parameter. The product of the six multiplier values is the task-specific SI score. Because the association between SI scores and UEMSDs may not be linear, SI scores are usually categorized into four ordinal "risk categories" (Moore & Garg, 1995).

The procedures described above are used to estimate a SI score (or risk category) for single-task jobs. For multi-task jobs, shift-specific SI scores are calculated by combining task-specific SI scores using a procedure such as the Cumulative SI, which is described below in the Research Design and Methods Section, 3.2.2.4.5.2.

3.1.3. Comparisons Between the SI and Other Exposure Assessment Methods

Prior to the current study, several previous studies have compared the SI to other established observational exposure assessment methods (e.g., Hand Activity Level, the Concise Exposure Index (OCRA), the Rapid Entire Body Assessment, and the Rapid Upper Limb Assessment) (S. Bao, Spielholz et al., 2006; Drinkaus, Sesek et al., 2003; Joseph et al., 2000; Moore et al., 2001; B. Silverstein et al., 2006; Wakula, 2005). But unlike the current study, the previous studies were not prospective in design and did not include comparisons to separate, quantitative estimates of exposure to each biomechanical risk factor (*e.g.* using surface electromyography (EMG) to estimate exposure to forceful exertions).

3.1.4. Specific Aims

The purpose of the project presented in this chapter was to compare measures of forceful exertion, repetition, and non-neutral wrist posture and to compare alternate multivariable models of associations between incident hand-arm symptoms and biomechanical exposures.

Specific Aims:

1. Compare measures of forceful exertion, repetition, and non-neutral wrist posture estimated with SI methods to measures of forceful exertion, repetition, and non-neutral wrist posture estimated with alternate exposure assessment methods.
2. To compare the effect of biomechanical exposures on incident hand-arm musculoskeletal symptoms adjusted for demographic and psychosocial confounders for a survival analysis model in which separate measures of force, repetition and non-neutral wrist posture were used to quantify exposures to biomechanical risk factors to a survival analysis model in which SI risk category was used to quantify exposures to biomechanical risk factors.

3.2. Research Design and Methods

From 2004 to 2008, a research team at the University of Iowa (UI) performed a cohort study of occupational risk factors for UEMSD among 387 household appliance manufacturing workers (the Iowa Study) ("Musculoskeletal disorders among manufacturing workers," Gerr, F., PI). The current study was a secondary analysis of previously collected data from the Iowa Study ("Musculoskeletal disorders among manufacturing workers," Gerr, F., PI). Archived demographic, personal, occupational psychosocial, biomechanical exposure, video and hand-arm health outcome data collected for the Iowa Study were used for the analyses presented in this chapter. To ascertain the SI data elements necessary for the current study, additional exposure information was extracted from archived video of study participants performing his/her task(s).

3.2.1. Study Population

All employees performing production work at a large manufacturing facility were eligible to participate in the Iowa Study. Iowa Study participants were included in the current study if they met all the Iowa Study requirements and 1) did not meet the Iowa Study criteria for a symptom event (Sx^+) at entry and 2) did not perform cyclic tasks with work cycles longer than six minutes.

3.2.2. Data Collection

3.2.2.1. Demographic, Personal, And Occupational Psychosocial Factors (Iowa Study)

Demographic, personal, and occupational psychosocial information was collected on two self-administered questionnaires completed by participants when they enrolled in the Iowa Study. The Job Content Questionnaire (JCQ) (Karasek, 1985; Karasek & Theorell, 1990) was used to estimate psychological job demands (demand), decision authority (control), coworker support, and supervisor support.

3.2.2.2. Daily Task Activities

Participants used pre-printed logs that were collected weekly to record information on 1) daily hours worked per task; 2) changes in work activities; 3) current work stress; 4) time spent performing non work-related hand intensive activities (e.g. gardening, playing video games); 5) time spent working at a second job; and 6) hand-arm symptoms.

3.2.2.3. Hand-Arm Symptoms

The Iowa Study assessed hand-arm symptom positive (Sx^+) case status with information related to hand-arm symptom quality, severity, and duration recorded on participants' weekly diaries. Hand-arm symptoms met the Iowa Study Sx^+ case definition if 1) pain, numbness, tingling, or burning symptoms were reported for the previous week, 2) symptom duration was at least 30 minutes, 3) reported pain level was at least 5 on a 0-10 visual analog scale or medication was used to alleviate pain, and 4) the symptoms were not attributed to an acute traumatic injury. The same Sx^+ case definition used for the Iowa Study was used for the current study.

3.2.2.4. Assessment of Exposure to Biomechanical Factors:

3.2.2.4.1. Overview

At entry to the Iowa Study, video recordings and surface electromyographic measurements of dominant upper extremity forearm muscle activity were obtained for participants for all tasks performed over a full shift. The simultaneous video recordings were made of sagittal (side view) and frontal plane (anterior or posterior) views of participants performing each of his or her tasks for ten to twenty minutes. In the laboratory, video clips were viewed and, for cyclic tasks, three representative work cycles were identified. Iowa Study investigators also used video recordings of participants performing his or her tasks and observation-based techniques to estimate task-specific exposures to repetition, and non-neutral wrist postures. Specifically, for the Iowa Study one exposure measure ascertained using Hand Activity Level (HAL) ratings and two other exposures measures were estimated using Multi-Video Task Analysis (MVTA) software to estimate percent time spent in non-neutral wrist posture (Table 3.1.).

For the current study, archived video recordings of Iowa Study' participants performing his/her task(s) were viewed to extract five SI task parameter estimates: intensity of exertion, hand-wrist posture, speed of work, duration of exertion, and efforts per minute. Participants' daily task logs were used to extract data on daily hours worked per task for the sixth SI task parameter, duration per day. A list of the exposure assessment methods and exposure measures used to estimate exposure to biomechanical risk factors in this study is presented in Table 3.1.

For Specific Aim 1, analyses to examine the relationship between SI and alternate measures of exposure to forceful exertions, repetition, and non-neutral wrist postures were conducted with the first five SI task parameters listed above compared to seven non-SI based exposure measures. Five of the seven non-SI based exposure measures were previously extracted for the Iowa Study, as mentioned above. Two other measures, percent duration of forceful exertions and rate of forceful exertions, were extracted for the current study as explained below.

For Specific Aim 2, unadjusted and multivariable survival analyses of the association between incident hand-arm symptoms and biomechanical exposures were conducted using weekly exposure metrics for SI risk category and the seven non-SI biomechanical exposure measures.

The following sections will explain the methods used to estimate biomechanical exposures for this study in the following order: forceful exertion methods, repetition methods, non-neutral wrist posture methods, and SI methods for computing and classifying SI scores to create SI risk categories.

3.2.2.4.2. Estimating Exposure to Forceful Exertions

3.2.2.4.2.1. Surface Electromyography Measures

For the Iowa Study, surface electromyography (EMG) was the direct exposure assessment method used to estimate exposure to forceful exertions. Among direct exposure assessment methods, EMG is considered one of the most accurate methods for estimating forceful exertions (Bhattacharya & McGlothlin, 1996; Bjelle, Hagberg, & Michaelsson, 1981; Burdorf & van der Beek, 1999; Kadefors et al., 1993; Kamen &

Caldwell, 1996; Malchaire et al., 1997; B. A. Silverstein, Fine, & Armstrong, 1987; van der Beek & Frings-Dresen, 1998). The amplitude of the EMG signal is used as an estimate of forceful exertion. In order to compare EMG measurements across people, however, a calibration or "normalization" procedure is necessary (DeLuca, 1997; Kamen & Caldwell, 1996; Spielholz, Silverstein, Morgan, Checkoway, & Kaufman, 2001). The Iowa Study procedures for EMG data collection, normalization and signal processing have been previously described (Fethke, Anton, Cavanaugh, Gerr, & Cook, 2007). Task-specific average root mean square (RMS) amplitudes were calculated for the muscle activity measures from the forearm extensors and flexors for each participant and normalized using a submaximal reference contraction (and reported as percent relative voluntary exertion [%RVE]). For the current study, among all tasks performed in a given week, the peak mean RMS amplitude (%RVE) was selected as the exposure metric for use in proportional hazards analyses.

3.2.2.4.2.2. Intensity of Exertion SI Task Parameter

Intensity of exertion is one of the six SI task parameters. To ascertain the intensity of exertion rating criterion, raters watched the video segments(s) for each task (in real time) several times. The intensity of exertion rating criterion (Light, Somewhat Hard, Hard, Very Hard, or Near Maximal) selected for a task was chosen based on the hand force observed during the most intense forceful exertion. For the current study, raters referred to a 0-10 visual analog scale (Figure 2.2) when selecting an intensity of exertion rating criterion (Light, Somewhat Hard, Hard, Very Hard, or Near Maximal) (Table 2.1.). Refer to Chapter 2 (Section 2.2.3.4. and Table 2.2.) for a more detailed explanation of SI parameter estimation procedures used for the current study.

3.2.2.4.3. Estimating Exposure to Repetition

The six measures of exposure to repetition presented in this section were estimated using four methods: HAL; detailed, frame-by-frame video observations (time-studies); and SI methods used to select a rating criterion category for SI task parameters. The methods used to create each exposure metric will be explained below.

3.2.2.4.3.1. HAL

The HAL is a reliable observation-based scale for estimation of hand/wrist repetition in cyclic work (Latko et al., 1997). From video clips of three representative work cycles, two trained investigators worked independently to ascertain a HAL rating for each task. Later, discrepancies were reconciled by consensus. Furthermore, a random sample of these results were selected and re-evaluated by a senior ergonomist to ensure the quality of the data. In repeated measures and survival analyses, HAL ratings were treated as continuous variables.

3.2.2.4.3.2. Measures Ascertained Using 'Time-Studies'

The video recordings of participants performing his or her tasks were used by trained observers who conducted detailed, frame-by-frame video observations (time-studies) of workers to count and time forceful exertions. Methods for selecting a particular video segment to be used for time-studies were explained in the previous chapter in Section 2.2.4.2. For this study, a *forceful exertion* was defined as a required, work-related hand/wrist motion, or action (*e.g.* using the hand to hold, manipulate, trigger, push, pull, or otherwise handle an object) that required a non-negligible level of force (≥ 8.9 N) (S. Bao, Howard, Spielholz, Silverstein, & Polissar, 2009; Stetson, *et al.*, 1991; Kapellusch, personal communication, May 12, 2008). Observers watched video clip(s) for each task to document the duration (ms) and frequency (forceful exertions/minute) of all forceful exertions. Raters watched the video segment(s) in real time and slow motion. Detailed (hh:mm:ss.f) observations of video start and stop times for each forceful exertion were used to calculate the duration of each forceful exertion and each video segment.

3.2.2.4.3.2.1. Percent Duration of Forceful Exertions

Task-specific values for percent duration of exertion were calculated by dividing the total duration of all forceful exertions by the duration of the observed video segments. A weekly percent duration of exposure was calculated for each participant, based on the task-specific values and the proportion of work hours spent performing each task.

3.2.2.4.3.2.2. Duration of Exertion SI Task Parameter

Using cut-points established for the SI (Table 2.1.), task-specific values for percent duration of forceful exertion were categorized to select rating criterion categories and multiplier values for the duration of exertion SI task parameter.

3.2.2.4.3.2.3. Rate of Forceful Exertions

Results from the detailed time-studies described above were also used to estimate task-specific rates of forceful exertions performed (exertions/minute). The rate of forceful exertions was calculated by dividing the number of forceful exertions counted by the duration of the observed video segments (min). A weekly rate of forceful exertions value was calculated for each participant, based on the task-specific values and the proportion of work hours spent performing each task.

3.2.2.4.3.2.4. Efforts per Minute SI Task Parameter

Task specific rates of forceful exertions were used to calculate a weekly exposure metric for rate of forceful exertions and to assign task-specific SI multiplier values for the efforts per minute SI task parameter.

3.2.2.4.3.4. Speed of Work SI Task Parameter

Speed of work is one of the six SI task parameters. To ascertain the speed of work rating criterion, raters watched the video segments(s) for each task (in real time) several times. Then, raters referred to the verbal descriptors (*e.g.* Normal, Fast, Very fast) for speed of work presented in Table 2.2. and selected the rating criterion that most accurately described the overall work pace observed during the video segment. Rating criterion estimates and multiplier values were estimated for the speed of work SI task parameter and these values contributed to SI score calculations, but speed of work was not used as a separate exposure metric for the current study.

3.2.2.4.4. Estimating Exposure to Non-Neutral Wrist Posture

3.2.2.4.4.1. Percent Time Spent in Non-Neutral Wrist Posture

Multi-Video Task Analysis software (Yen & Radwin, 2002) is a video-based observational method that allows the observer to quantify, for selected joints, the time spent in awkward postures (Spielholz et al., 2001). The Iowa Study used MVTA to evaluate each participant's percent time spent with wrists extended or flexed greater than 30°. Wrist posture categorizations were ascertained by trained investigators while viewing video clips of three representative work cycles. Wrist posture categorizations were coded independently by two investigators and discrepancies were reconciled by consensus. Furthermore, a random sample of these results were selected and re-evaluated by a senior ergonomist to ensure the quality of the data. For the current study, the two fundamental wrist posture variables used as separate measures were percent time spent in wrist extension > 30° and percent time spent in wrist flexion > 30°. Time-weighted averages of these variables were used for proportional hazards analyses.

3.2.2.4.4.2. Hand-Wrist Posture SI Task Parameter

The qualitative method used to select hand-wrist posture rating criterion category (Very Good, Good, Fair, Bad, Very Bad) was similar to the method used for intensity of exertion. Trained observers watched the video segments and, using the verbal descriptors and the wrist extension, flexion, and ulnar deviation angles presented in Table 2.2., selected a hand-wrist posture rating criterion category to characterize the most common wrist posture used during the task.

3.2.2.4.5. Estimating SI Risk Category

3.2.2.4.5.1. Estimation of Preliminary SI Score

The preliminary SI score includes all SI parameters except the duration per day SI task parameter. A consensus approached was used to ascertain SI parameter final multiplier values for intensity of exertion, hand-wrist posture, speed of work, percent duration of exertion, and efforts per minute SI task parameters. For the consensus approach, each rater viewed the video recordings independently and used the methods described above to select initial rating criterion and multiplier values for the SI task parameters (Table 2.1.). When the two initial multiplier values were not identical, then the raters met, watched the video segments, and agreed upon a final multiplier value.

3.2.2.4.5.2. Calculating Multi-Task SI scores

As indicated previously, task-specific SI scores are the product of the six multiplier values (one value per SI task parameter). For multi-task jobs, shift-specific SI scores were calculated by combining task-specific preliminary SI scores (the product of all SI task parameter multiplier values except duration per day). The duration per day SI task parameter was selected based on task log information on daily hours worked per task per shift and was used to calculate the multi-task SI score, as described below.

In the literature, formulas used to calculate SI scores vary between investigators; however there seems to be agreement on the following principles and assumptions for calculating SI scores for multi-task jobs (Stephen Bao et al., 2009; Garg, 2006):

1. The multi-task job SI score should be greater than or equal to the highest SI score among all tasks performed.

2. For each additional task performed in a multi-task job, an "incremental increase" in exposure to biomechanical risk factors is produced.
3. The incremental increase in exposure associated with each additional task performed is dependent on the magnitude of the SI task parameter ratings for additional tasks performed.
4. The incremental increase in exposure associated with each additional task performed is independent of exposure measures for preceding tasks.

In general terms, for the current study all SI scores were calculated by taking the sum of 1) the highest SI score among all tasks performed per shift, and 2) the incremental increases in exposure for each additional task, as estimated by the SI. A detailed description of the formulas and procedures used to calculate SI scores with the CSI computation method is presented in Appendix D.

3.2.2.4.5.3. Assigning SI Risk Category

Because the association between SI scores and UEMSDs was not linear in the sample studied by Moore and Garg (1995), SI score values are usually categorized into four ordinal "risk categories" to assist in interpretation. The empirically derived SI cut-points (8.72, 13.5, and 18.56) developed in Chapter 2 of this dissertation for the Empirical SI classification method were used to assign each participant a daily SI risk category for each workday. The "Empirical SI risk category" variable from Chapter 2 is referred to as the "SI risk category" variable in the current chapter. The peak daily SI risk category for each week (Monday – Sunday) of observation was selected and used as the SI risk category metric used for all statistical analyses.

3.2.2.4.5.4. Missing Exposure Data Procedures

In the current study, when there were any missing exposure data for a symptom event week, all other exposure metrics were re-coded to missing for the same week. This was necessary to ensure that all multivariable models included equal numbers of symptom positive weeks.

3.2.3. Statistical Analysis

3.2.3.1. Power Analysis

Prior to data extraction, a power analysis was performed using conservative assumptions of an incidence rate of 22.5% among participants in the lowest SI risk exposure category (quartile) and an odds ratio of 2.0 when compared to the highest SI risk category. Based on these assumptions, a sample size of 270 was needed for the proposed study to have 80% power (Lenth, 2006-9).

3.2.3.2. Descriptive Statistics

Descriptive statistics were calculated for all participants and stratified by gender for time independent (participant-specific, N = 276) and time-varying (participant weeks = 8826) demographic, personal, and psychosocial/work organization covariates. Descriptive statistics were also calculated for time independent, task-specific (number of tasks = 1020) biomechanical exposure variables and for time-varying (participant weeks = 8826), weekly biomechanical exposure variables by hand-arm symptom status.

3.2.3.3. Repeated Measures Analyses

Specific Aim 1: Compare measures of forceful exertion, repetition, and non-neutral wrist posture estimated with SI methods to measures of forceful exertion, repetition, and non-neutral wrist posture estimated with alternate exposure assessment methods.

To address the first specific aim of this study, several repeated measures models were used to compare task-specific estimates of exposure to forceful exertions, repetition, and non-neutral wrist postures ascertained using SI methods to alternate exposure assessment methods. Seven general linear mixed-effect models for repeated measures were used to quantify differences between different task-specific exposure metrics used to estimate exposure to the same biomechanical risk factor (forceful exertions, repetition, and non-neutral hand-wrist postures) (Table 3.1). For all models, participant was a repeated, random factor. Overall, the compound symmetric variance/covariance structure was the best fit (smallest Akaike information criterion (AIC) values).

A different continuous measure of exposure was used as the dependent variable for each repeated measures analysis. The categorical SI task parameters used as the independent variable for each model were: intensity of exertion for comparisons between forceful exertion measures (two models), speed of work for comparisons between repetition measures (three models), and hand-wrist posture for comparisons between non-neutral wrist posture measures (two models). For all repeated measures analyses, pairwise comparisons were conducted to identify SI task parameter rating criterion categories in which least squares mean values of the dependent variable were statistically significantly different from one another ($\alpha = 0.05$).

3.2.3.3.1. Forceful Exertion Task Exposure Measures

The two EMG variables (forearm extensors and forearm flexors) (peak mean %RVE) were analyzed as the dependent variables in analyses of forceful exertion. For analyses of task-specific forceful exertion exposure measures, the SI intensity of exertion task parameter was the independent variable in repeated measures analyses. Intensity of exertion was a within-subjects factor with five fixed levels: *Light, Somewhat Hard, Hard, Very Hard, Near Maximal.*

3.2.3.3.2. Repetition Task Exposure Measures

The dependent variables for repetition exposure measures were percent duration of forceful exertions, rate of forceful exertions and HAL. For analyses of task-specific repetition metrics, the SI speed of work task parameter was the independent variable in repeated measures analyses. Speed of work was a within-subjects factor with three fixed levels: *Very Slow/Slow/Fair, Fast, and Very Fast.* Additionally, Pearson correlation coefficients (*r*) were calculated between weekly percent duration of forceful exertions, rate of forceful exertions, and time-weighted average HAL values.

3.2.3.3.3. Non-Neutral Wrist Posture Task Exposure

Measures

The dependent variables for measures of non-neutral wrist posture were wrist extension > 30° (percent time) and wrist flexion > 30° (percent time). For analyses of task-specific non-neutral wrist postures, the SI hand-wrist posture task parameter was the independent variable in repeated measures analyses. Hand-wrist posture was a within-subjects factor with four fixed levels: *Very Good/Good, Fair, Bad, Very Bad.*

3.2.3.4. Unadjusted Survival Analyses

For the current study, instantaneous risk and relative risk (*i.e.,* relative hazard) were estimated using survival analysis methods (Cox & Oakes, 1984; Kalbfleisch & Prentice, 1980). Survival time was defined as time from enrollment to outcome. Symptom free participants were censored at the time they were lost to follow-up or when the study ended. Weeks to the hand-arm symptom outcome was used as the dependent variable for unadjusted and multivariable analyses. Extended Cox models (Cox & Oakes, 1984) were used to accommodate time-varying independent variables and covariates.

Separate unadjusted analyses were performed to examine the relative risk (*i.e.* hazard ratios) of incident hand-arm symptoms associated with each covariate (demographic, personal, and psychosocial/work organization) and each SI risk category structure (*i.e.* Original, Empirical) for the entire facility and stratified by gender. The proportional hazards assumption was tested for all time independent covariates.

Separate unadjusted analyses were performed to examine the relative risk of incident hand-arm symptoms associated with each of the seven time-varying, continuous independent variables (Table 3.1.) that were later included in the multivariable Separate

Measures Model: forearm extensor muscle activity, forearm flexor muscle activity, HAL, percent duration of forceful exertions, rate of forceful exertions, percent time wrist extension, and percent time wrist flexion. The eighth independent variable, SI risk category, was a categorical variable with four levels (Category 1 – Category 4) and was later included in the multivariable SI Model. Dummy variables were created for the SI risk category metric and, because the lowest SI scores were assigned to Category 1, that category was used as the referent category for unadjusted and multivariable survival analyses models.

3.2.3.5. Covariate Selection for Multivariable Models

The covariates selected for the final multivariable Separate Measures and SI Models were selected using the following methods. Demographic, personal, and psychosocial/work organization covariates with < 0.2 probability of association with hand-arm symptoms were retained as potential confounding variables. All potential confounding variables were included in two full multivariable models. The independent variables of interest in the first model, the Separate Measures Model, were the seven separate, continuous measures of biomechanical exposure and the independent variable in the second model, the SI Model, was SI risk category. Potential confounding variables were removed from each full model one at a time, starting with the least statistically significant covariate. All covariates were subject to removal. Potentially confounding variables were considered actual confounding variables when the reduced model compared to the full model resulted in 1) a change of 15% or greater in the hazard ratio of any of the independent variables (Kleinbaum & Klein, 2005) or 2) a lower Akaike Information Criterion (AIC) value (Akaike, 1973). The AIC value is used to ascertain adequacy of fit for statistical models. Lower AIC values indicated a better-fitting model. Any actual confounder identified for either model (Separate Measures Model or SI Model) was included in both final multivariable models. The same covariate selection procedures outlined in the previous paragraph were also used to build separate multivariable models for male and female participants.

3.2.3.6. Multivariable Survival Analyses

The final multivariable models were then used for analyses to estimate the association between incident hand-arm symptoms and two alternate biomechanical exposure models: 1) seven separate measures of forceful exertions, repetition, and non-neutral wrist posture (Separate Measures Model) or 2) SI risk category (SI Model).

3.2.3.6.1. Separate Measures Model vs. SI Model

Specific Aim 2: To compare the effect of biomechanical exposures on incident hand-arm musculoskeletal symptoms adjusted for demographic and psychosocial confounders for a survival analysis model in which separate measures of force, repetition and non-neutral wrist posture were used to quantify exposures to biomechanical risk factors to a survival analysis model in which SI risk category was used to quantify exposures to biomechanical risk factors.

To address the specific aim of the current study, AIC differences and a strength of the evidence approach (Burnham & Anderson, 1998) were used to compare the Separate Measures Model and the SI Model. Model fit statistics, such as AIC values, provide information for the entire model and not solely for variables of interest to the researcher. For the current study, the objective was not to identify the final multivariable model with the best overall model fit (lowest AIC value). The goal of this study was to isolate the contribution to model fit made by the biomechanical exposure variables included in each model as opposed to the confounding variables. To achieve this objective, two AIC differences were calculated and compared. First, the difference in AIC values was calculated for the final Separate Measures Model compared to a reduced model that included only the seven biomechanical risk factors in the model (no confounders) (AIC difference_{SM}). Second, the difference in AIC values was calculated for the final SI Model compared to the unadjusted SI model (AIC difference$_{SI}$). Finally the value of AIC difference$_{SM}$ was compared the value of AIC difference$_{SI}$, where the largest value represented the biomechanical model that accounted for more of the variability in the data that could be attributed to biomechanical exposure measures rather than confounders. Also, the statistically and practically significant associations between the independent variable(s) and incident hand-arm symptoms were considered.

3.2.3.6.2. Gender Interaction

Some interactions were observed between incident hand-arm symptoms, gender and several covariates. Therefore, the association between incident hand-arm symptoms and biomechanical exposures as estimated by either the Separate Measures Model or the SI Model was evaluated separately for male and female participants.

All analyses were performed using SAS® version 9.2.

3.3. Results

3.3.1. Study Sample

Time independent and time-varying demographic, personal health and occupational characteristics for participants (N = 276) in the current study are presented in Chapter 2, Table 2.3. Six of the 282 Iowa Study participants who were symptom negative upon entry were excluded from the current study because their job task(s) could not be evaluated with the SI (cycle times lasted more than six min). The average age of participants was 42.8 yr (SD = 10.0 yr), 48% were female, and the average length of employment at the facility was 16.3 yr (SD = 11.2 yr). The incidence of hand-arm pain was 57 per 100 person/years.

The participation rate was 52%. Some information was collected from non-participants. Compared to participants, the mean age of non-participants was 2 years younger, the mean number of years worked at the facility was about 4 years less and a greater proportion were men (61% vs. 49%) who worked on second shift (50% vs. 32%).

3.3.2. Biomechanical Exposure Methods Comparisons

3.3.2.1. Descriptive Statistics

Descriptive statistics for measures of time independent, task-specific (number of tasks = 1020) exposure measures and weekly, time-varying exposure measures (number of participant weeks = 8826) are presented in this section. Descriptive statistics are presented separately for task-specific forceful exertion measures, repetition, non-neutral wrist posture measures, and SI risk category.

3.3.2.1.1. Forceful Exertion Measures

Descriptive statistics for all time independent, task-specific exposure metrics are presented in Table 3.2. For task-specific EMG measures, the mean forearm extensor muscle activity was 54 %RVE (SD = 28 %RVE) and mean forearm flexor muscle activity was 104 %RVE (SD = 88 %RVE) (Table 3.2). For approximately ninety percent of tasks, the Light or Somewhat Hard rating criterion category was selected for the SI intensity of exertion task parameter.

Descriptive statistics for forceful exertion measures and all other weekly, time-varying exposure metrics are presented by hand-arm symptom status in Table 3.3. The mean weekly peak forearm extensor values were 61 %RVE (SD = 33 %RVE) for Sx^- and 67 %RVE (SD = 37 %RVE) for Sx^+ (Table 3.3.). Additionally, forearm flexor values were 125 %RVE (SD = 99 %RVE) for Sx^- and 128 %RVE (SD = 113 %RVE) for Sx^+.

3.3.2.1.2. Repetition Measures

The task-specific mean HAL for the facility was a rating of 5 (SD = 1.3) on a 0 to 10 scale (Table 3.2). This moderate HAL value is consistent with the SI speed of work results. For the SI speed of work task parameter, more than 90% of tasks were assigned a multiplier value of 1.0 (Very Slow, Slow, or Fair speed of work) (Table 3.2.). No tasks in the study were characterized as Very Fast. If the SI rating criterion category cut-points for duration of exertion and efforts per minute SI task parameters (Table 2.1.) were used to categorize the mean values observed for percent duration of forceful exertions and rate of forceful exertions, then both weekly measures would be assigned to the middle SI rating criterion category. Percent duration of exertion was less than 30% for 33% of tasks and was between 30% and 49% for 48% of tasks. Two-thirds of the efforts per minute estimates were between 9 and 19 efforts per minute. In general, a somewhat broad distribution of tasks by SI task parameter rating criterion category was observed for duration of exertion and efforts per minute compared to other SI task parameters, although no statistical test was conducted to test this observation.

3.3.2.1.3. Non-neutral Wrist Posture Measures

Overall, the percent time spent in non-neutral wrist postures was relatively low. Among this sample of 1020 tasks, the mean percent time observed with wrist extension > 30° was 10% (SD = 9.4%) and with wrist flexion > 30° was 4% (SD = 4.2) (Table 3.2). For the SI hand-wrist posture task parameter, 36% of tasks were characterized as Very Good or Good and 48% were characterized as Fair (Table 3.2). Similar to the task-specific means, the time-weighted average weekly value for percent time spent in wrist extension > 30° was 9.8% and for percent time spent in wrist flexion > 30° was 2.9% (data not shown).

3.3.2.1.4. SI Risk Category

The frequency distribution of participants' weekly SI risk category by hand-arm symptom status is presented in Table 3.3. Development of the Empirical SI risk category cut-points used for the current study is described in the previous chapter (Section 2.2.3.6., Assigning SI Risk Categories). The methods ensure that the number of Sx^+ participant weeks is approximately equal across the four Empirical SI risk categories. Comparisons between Empirical SI risk category and other exposure metrics will be presented in the next section.

3.3.2.2. Associations between Alternate Biomechanical Exposure Measures and SI Task Parameter Estimates

3.3.2.2.1. Forceful Exertions Measures

Mean forearm muscle activity values are presented by SI intensity of exertion rating criterion category in Figure 3.1. Across the five intensity of exertion rating criterion categories, task-specific least mean square mean %RVE estimates for forearm extensors did not vary significantly among the Light, Somewhat Hard, Hard, and Very Hard rating criterion categories. Due to sparse numbers of tasks in each category, least mean squares forearm muscle activity estimates for the Very Hard (number of task = 15) and Near Maximal (number of tasks = 4) rating criterion categories were imprecise. In contrast to the extensor EMG results by SI intensity of exertion rating criterion category, statistically significant differences were observed among SI intensity of exertion rating criterion categories for least squares mean forearm flexor estimates. Specifically, for tasks in the Light rating criterion category, least squares mean forearm flexor estimates were statistically significantly lower than estimates for tasks in the Somewhat Hard or Hard categories. All pairwise comparisons between exposure assessment methods were conducted using general linear mixed-effect models for repeated measures ($\alpha = 0.05$).

3.3.2.2.2. Repetition Measures

Least squares mean estimates for percent duration of forceful exertion, rate of forceful exertions, and HAL are presented by SI speed of work rating criterion category in Figure 3.2. In the figure, data for the Very Slow, Slow, and Fair categories were collapsed into one category because the categories shared the same multiplier value (1.0).

Statistically significant differences were observed for least squares mean estimates for rate of forceful exertions and HAL between the Very Slow/Slow/Fair and the Fast SI speed of work rating criterion categories, but no statistically significant difference was observed for percent duration of forceful exertions. Pearson correlation coefficients (*r*) among weekly measures for duration of forceful exertion, rate of forceful exertions, and time-weight average HAL are presented in Table 3.4. No strong linear associations were observed between any of the three repetition metrics ($r < 0.50$ for all correlations).

3.3.2.2.3. Non-Neutral Wrist Posture Measures

Among the 1020 tasks, at least 90% of participants' time was spent in wrist extension or flexion < 30° and about 85% of tasks were characterized as Fair (Non-neutral) or better using the SI hand-wrist posture task parameter rating criterion category.

Least squares mean estimates for percent time in wrist extension and flexion are presented by SI hand-wrist posture rating criterion category in Figure 3.3. Similar to the speed of work task parameter, because the multiplier values for the Very Good and Good hand-wrist posture rating criterion categories were the same value, those two categories were pooled in Figure 3.3. Least squares mean wrist extension estimates were statistically significantly different for pairwise comparisons between the higher exposure categories (Bad or Very Bad) compared to each other and compared to the two lower exposure categories (Very Good/Good, Fair). Wrist flexion results were less consistent. Least squares mean wrist flexion estimates were not statistically significantly lower for pairwise comparisons between the best (Very Good/Good) and worst (Very Bad) hand-wrist posture exposure categories. However, in pairwise comparisons between least squares mean wrist flexion estimates for the Very Good/Good hand-wrist posture category and the Fair or Bad categories, observed differences in percent time were statistically significantly lower for the Very Good/Good category.

3.3.3. Survival Analyses

3.3.3.1. Crude Associations

Separate unadjusted models of association between hand-arm symptoms and personal, demographic, psychosocial, work organization, forceful exertion, repetition, non-neutral wrist posture, and SI measures were conducted. To maintain equal numbers of Sx^+ events for all biomechanical exposure models, six weekly SI risk category values were coded as missing during a Sx^+ event week because data was missing for one or more of the separate measures of biomechanical exposure during that week.

3.3.3.1.1. Personal, Demographic, Psychosocial and Work Organization Characteristics

Unadjusted associations between hand-arm symptoms and potential demographic, personal, and psychosocial/work organization confounders are presented in Table 2.6. Potential confounders ($p < .20$) identified based on these analyses were: sex, height, co-morbidities, previous hand-arm symptoms, hours worked at second job, hours per week of non-work-related hand intensive activity, job strain quadrant, weekly job stress, and weekly job change.

3.3.3.1.2. Biomechanical Exposure Measures

Unadjusted associations between hand-arm symptoms and biomechanical exposure measures are presented in Table 3.5. The only statistically significant unadjusted association observed between hand-arm symptoms and one of the eight biomechanical exposure measures was for SI risk category. Specifically, a statistically significant 71% increase in relative risk (*i.e.* HR) was observed for SI risk Category 3 compared to Category 1. Two other associations approached statistical significance – a 70% increased risk for SI risk Category 2 compared to Category 1 ($p = .10$) and a 1% increase in risk for every 1% increase in percent duration of forceful exertions ($p = .13$).

3.3.3.2. Multivariable Associations Between Hand-Arm Symptoms and Biomechanical Exposures

Multivariable associations between time to developing hand-arm symptoms are presented for two alternate biomechanical models (Separate Measures Model and SI Model) in Table 3.6. The Separate Measures Model estimated exposures to forceful exertions, repetition, and non-neutral wrist postures separately with seven exposure variables (forearm extensor muscle activity, forearm flexor muscle activity, HAL, percent duration of forceful exertions, rate of forceful exertions, percent time wrist extension, and percent time wrist flexion). The SI Model used SI risk category to estimate biomechanical exposures. Both biomechanical models included the following covariates: sex, previous hand-arm symptoms, hours worked at second job, hours per week of non-work-related intensive hand activity, weekly job stress, and weekly job change. The following three sections will present estimates of association and model fit statistics (AIC differences) for comparison of the Separate Measures Model to the SI Model. Statistical interactions between gender, hand-arm symptoms and the biomechanical exposures will also be presented for Separate Measures and SI Models.

3.3.3.2.1. Separate Measures Model

Among the seven separate biomechanical exposure variables in the Separate Measures Model, a statistically significant 2% increase in risk of developing hand-arm symptoms was observed for every 1% increase in percent duration of forceful exertions. For example, a worker whose work week was characterized by a measure of 50% for percent duration of forceful exertions would have about an 80% increased risk of developing hand-arm symptoms compared to a worker with a 20% measure for percent duration of forceful exertion for the week.

3.3.3.2.2. SI Model

For the SI Model, a more than two-fold (HR = 2.23), statistically significant increase in relative risk of developing hand-arm symptoms was observed for SI risk Category 3 compared to Category 1. Non-statistically significant increases in risk were observed for SI risk Category 2 and Category 4.

3.3.3.2.3.The Effect of Gender

To test for interactions between gender, hand-arm symptoms and the biomechanical exposures for both the Separate Measures and SI Models, separate multivariable models, with different covariates, were built for male and female participants (Separate Measures $Model_{Male}$, Separate Measures $Model_{Female}$, SI $Model_{Male}$, and SI $Model_{Female}$). Consistent with the results for the full sample, for Separate Measures $Model_{Male}$ and Separate Measures $Model_{Female}$ the only statistically significant association among the seven biomechanical exposure measures was for the percent duration of forceful exertion measure in Separate Measures $Model_{Female}$ (HR = 1.03, p = .01, data not shown). Among male participants percent duration of forceful exertions approached statistical significance (HR = 1.02, p = .10, data not shown). Other than these differences, effect modification by gender was not evident for the Separate Measures Model. In contrast, when biomechanical exposures were estimated with SI risk category, modification of the effect of SI risk category on hand-arm symptoms by gender was observed. Specifically, for associations between SI risk category and incident hand-arm symptoms among women, higher HRs and stronger associations (Category 2_{Female}, HR = 2.11, p = .08; Category 3_{Female}, HR= 2.65, p = .01; Category 4_{Female}, HR = 2.06, p = .07) were observed compared to a model examining associations between SI risk category and incident symptoms among men (Category 2_{Male}, HR = 1.73, p = .31; Category 3_{Male}, HR = 2.04, p = .14; Category 4_{Male}, HR = .68, p = .07). Interactions between gender, SI risk category, and hand-arm symptoms are presented in more detail in the Results and Discussion sections of Chapter 2 and Figure 2.6.

3.3.3.2.4.Model Fit for Biomechanical Exposure Measures

The overall strength of the evidence supported the use of the SI over the seven separate biomechanical exposure metrics as risk factors for hand-arm symptoms. For this sample of workers, the evidence supporting the survival analysis model in which the effect of biomechanical exposures on incident hand-arm symptoms adjusted for demographic and psychosocial/work organization confounders was estimated using SI risk category (AIC difference_{SI} = 97.165) was stronger compared to a survival analysis model in which the effect of biomechanical exposures was estimated using separate measures of force, repetition and non-neutral wrist postures (AIC difference_{SM} = 95.463) (Table 3.6). When interpreting AIC differences in this context, the absolute difference between the differences (1.702) indicates evidence in support of the model with the larger change in AIC values – the SI Model. The relative value of the differences is irrelevant. Furthermore, statistically significant associations with incident hand-arm symptoms were observed for SI risk category, especially among women.

In contrast, the overall model fit statistics supported the Separate Measures Model (AIC = 829.046), as a substantially better fit to the data overall compared to the SI Model (AIC = 924.509) (Burnham & Anderson, 1998). Compared to the SI risk category maximum likelihood parameter estimates in the SI Model, the parameter estimates for the biomechanical exposure measures in the Separate Measures were substantially more precise, which was a contributing factor to the overall model fit results that favored the Separate Measures Model. Also, compared to the SI risk category, more of the variability of the confounders was accounted for when the seven separate measures were used as estimates of biomechanical exposure. In summary, the SI Model accounted for more of the variability that could be attributed to biomechanical exposures and the Separate Measures Model was a better overall fit to the data.

3.4. Discussion

3.4.1. Overview

Forceful exertions, repetition, and non-neutral wrist postures are well established risk factors for hand-arm symptoms (Bernard, 1997; National Research Council - Institute of Medicine, 2001). However, despite a relatively high incidence of hand-arm symptoms among study participants, only two of eight biomechanical exposure measures were associated with incident hand-arm symptoms. Specifically, SI risk category was associated with incident hand-arm symptoms, especially among women. Also, the percent duration of forceful exertions exposure metric appeared to have some value. For every 1% increase in percent duration of forceful exertions, a 2% increase in risk of incident hand-arm symptoms was observed.

Aside from the percent duration of exertion metric, almost no association between incident hand-arm symptoms and the seven separate biomechanical exposure measures was observed. Additionally, when SI task parameter estimates of biomechanical risk factors were compared to alternate measures of the same risk factor construct (*e.g.* forceful exertions), associations were observed only between alternate metrics used to quantify exposure to non-neutral wrist postures. These results will be discussed in more detail in the next section.

The empirical evidence in the aforementioned multivariable models favored using the categorical SI metric to characterize biomechanical exposures compared to separate measures of exposure. Unexpectedly, substantially more variability in the data overall (including confounding variables) was accounted for by the model that included separate measures of biomechanical exposures. The contrasts in strength of associations with incident hand-arm symptoms and evidence of multivariable model fit between SI biomechanical exposure estimates and separate measures of exposure for evidence will be discussed below in Sections 3.4.3. and 3.4.4.

3.4.2. Associations between Biomechanical Exposure Measures

Several differences were observed between models examining association between the SI and incident hand-arm symptoms and models examining associations between separate measures of biomechanical exposures and incident hand-arm symptoms. If biomechanical exposures were associated with incident hand-arm symptoms in this population, then the lack of association observed between incident hand-arm symptoms and most of the exposure metrics in the Separate Measures Model may indicate that several metrics (e.g. the EMG and HAL) selected for this study were poor characterizations of exposure among these participants.

In this study, for each biomechanical risk factor construct, SI task parameter ratings were compared to exposure estimates ascertained using alternate biomechanical exposure assessment methods. Associations between separate metrics designed to assess the same risk factors were observed only for those measuring non-neutral wrist posture. In particular, a monotonic increase in the mean percent time spent in wrist extension and flexion > 30° was observed across SI hand-wrist posture categories (Very Good/Good, Fair, Bad, Very Bad).

In contrast, few associations were observed between any of the task-specific measures of forceful exertions and the SI intensity of exertion task parameter rating categories. However, based on the distribution of weekly EMG values for the forearm muscles and the frequency distribution of tasks across the five intensity of exertion SI task parameter rating criterion categories, the magnitude of the force requirements for most tasks observed for this study appeared to be fairly moderate (*e.g.* Light or Somewhat Hard SI task parameter rating criterion). For measures of repetition, very little association was observed between the three continuous repetition metrics. If, in reality, forceful exertions, repetition, or hand-wrist posture were associated with incident hand-arm symptoms among participants in this sample, then it is possible that the specific exposure metrics chosen for the Separate Measures Model did not characterize these risk factors in a biomechanically meaningful way. The forced linear dose-response relationship in the Separate Measures Model was another possible explanation for the observed contrasts with the SI Model and will be discussed below.

3.4.3. Associations with Incident Hand-Arm Symptoms

Evidence of associations between incident hand-arm symptoms and biomechanical exposure estimates using the SI were more compelling than the evidence of associations between incident hand-arm symptoms and biomechanical exposure estimates using the separate measures. In particular, somewhat strong associations were observed among female participants between hand-arm symptoms and SI risk category. In contrast, HRs for the SI Model among men were not statistically significant.

In contrast, other than the percent duration of exertion metric, the Separate Measures Model was not very useful for predicting incident hand-arm symptoms. HRs of approximately 1.0 were observed among six of seven exposure measures. For the seventh measure, percent duration of forceful exertions, an appreciable increase in risk of hand-arm symptoms was observed for each unit increase in weekly percent duration of forceful exertions measures.

The lack of associations between hand-arm symptoms and the remaining six biomechanical exposures in the Separate Measures Model are inconsistent with the literature. Consequently, it is possible that the exposure metrics selected for the Separate Measures Model were not appropriate measures of exposure to biomechanical risk factors among these participants.

3.4.4. Comparison of Model Fit

A strength of the evidence approach (Burnham & Anderson, 1998) was used to compare multivariable models of association between incident hand-arm symptoms and exposures. In multivariable models examining associations between biomechanical exposures and incident hand-arm symptoms adjusted for demographic and psychosocial confounders, the amount of variability in the model that could be attributed to biomechanical exposures was greater for the SI Model than for the Separate Measures Model. In contrast, overall model fit, as measured by AIC, supported the Separate Measures Model (lower AIC) over the SI Model. This result was unexpected because in comparisons between alternate multivariable models, the model with the lower AIC value would also typically be characterized by higher and more statistically significant measures of relative risk (e.g. HR) compared to the model with the higher AIC value. But in the current study the opposite was observed. Several explanations for these contradictory findings will be discussed in this section.

3.4.4.1. Individual vs. Group Exposure Estimates

One contributing factor to the apparently contradictory findings in support of the Separate Measures Model was the use of homogenous exposure groups for assigning task-specific SI task parameter multiplier values. Specifically, similar tasks were first grouped and then a common SI parameter was assigned to all tasks in each group after assessment of a subsample of tasks from each group. This introduced error into the SI Model by artifactually reducing the observed variability in comparison to the true variability. In contrast, Iowa Study investigators estimated exposure values separately for each of the 1020 tasks performed among the 276 participants. To avoid systematic error in exposure rating, SI raters were blinded to participant health outcome during data extraction. Therefore, measurement error associated with the use of homogenous exposure groups is expected to be non-differential. Non-differential error in exposures estimation will attenuate observed associations between exposures and health outcomes.

3.4.4.2. The Effect of Demographic and Psychosocial/Work Organization Confounders

Inconsistencies in model evaluation between model fit methods compared to strength of association approaches may be attributable to differences in associations between the biomechanical exposure variables in the Separate Measures Model and the six covariates in the models. Specifically, in multivariable models examining associations between biomechanical exposures and incident hand-arm symptoms adjusted for demographic and psychosocial confounders, the variability in the model that could be attributed to the demographic and psychosocial variables was greater for the Separate Measures Model than for the SI Model (data not shown).

It is reasonable to infer that more variability was explained in a model that included individual measures of health outcomes and confounders when biomechanical exposures were quantified with individual exposure measurements (Separate Measures Model) compared to a model that quantified biomechanical exposures with homogenous exposure group measurements (SI Model). The main goal of this study was to examine evidence of association between incident hand-arm symptoms and *biomechanical* exposures, not covariates. Consequently, although the Separate Measures Model explained more variability in the model overall, the evidence does not support using these particular separate measures to estimate exposure to biomechanical risk factors. To more fully adjust for confounders in future epidemiologic studies, it may be worthwhile to conduct SI ratings separately for each individual.

3.4.4.3. Assumptions of Linearity

One possible explanation for the inconsistent associations that were observed between incident hand-arm symptoms and the two alternate biomechanical models is that the relationship between biomechanical exposures and incident hand-arm symptoms may not be linear. The SI Model and the Separate Measures Model required different assumptions about the shape of the dose-response curve for biomechanical exposures and hand-arm symptoms, which also may have influenced the model fit results. Compared to using several continuous variables to estimate exposure separately for each biomechanical risk factor, using a single, ordinal, categorical variable (SI risk category), to characterize several biomechanical exposures was both an advantage and a disadvantage. An advantage is that no assumption of linearity was necessary when modeling the SI with dummy variables. However, collapsing a continuous measure (SI score) into categories does result in some loss of information. The Separate Measures Models, in which each exposure metric was modeled as a continuous variable, assumed a linear exposure-response relationship. It appears that the increase in precision resulting from use of continuous measures did not offset the disadvantage of the linear assumption.

3.4.4.4. Measurement Error in SI Methods

For this study, SI methods introduced several sources of non-differential measurement error in the final SI exposure metric – peak daily SI risk category per week. For example, the qualitative methods used to estimate exposure for the SI task parameters associated with forceful exertion and non-neutral wrist posture exposures (intensity of exertion and hand-wrist posture) were less objective compared to quantitative measures used to estimate the percent duration and efforts per minute SI task parameters. Also, the SI task parameter multiplier values assigned to each SI task parameter introduced another source of measurement error to the SI scores because the values were chosen by Moore and Garg (1995) and may not be appropriate for this cohort. Additionally, the CSI computation method used to calculate SI scores for multi-tasks jobs has not been validated empirically. Finally, the cut-points used to create the SI risk categories were validated in one study (Chapter 2) among the same sample used for the current study. Considering the many sources of non-differential measurement error affecting the final SI risk category metric, the increased risk for hand-arm symptoms observed for SI risk category was likely an underestimate.

3.4.5. Limitations

The findings of this study suggest that the SI may predict future hand-arm pain among workers performing single-task and multi-task manufacturing jobs similar to those performed by the study sample. However, about 90% of the intensity of exertion task ratings at this facility were rated “Light” or “Somewhat Hard.” Observed associations between hand-arm pain and SI have been attenuated due to the limited range of exposure to forceful hand-arm work observed at this facility.

Only manufacturing workers were included in this study, therefore it is uncertain whether the associations between SI risk category and incident hand-arm symptoms can be generalized to other industries. Due to sample size limitations, the current study was not able to examine associations between the SI and incident UEMSDs.

Another limitation in the current study was sample size. Among epidemiologic studies of musculoskeletal symptoms and disorders, a sample size of 276 is not considered small. Regardless, statistical power in this study was limited due to sparseness within some strata of categorical variables. Estimates of association for the SI by gender were especially limited by sample size considerations.

Additionally, we recognize that the participation rate of 52% may have resulted in sample distortion. It is possible that the associations between exposures and outcome among participants were different than among non-participants. However, the Iowa Study participation rate of 52% is consistent with the experience of many investigators conducting prospective cohort studies.

Furthermore, we do not believe that the difference in associations observed between the original SI category structure and hand-arm musculoskeletal symptoms and the empirical SI and hand-arm musculoskeletal symptoms was an artifact of participation. For this to occur, participation would have been related differentially to the association between the two SI categorization methods and MS symptoms. No plausible mechanism for such differential participation could be hypothesized.

3.4.6. Future Research

The research presented in the current study addressed gaps in the literature regarding the lack of methodologically rigorous epidemiologic evidence to support the use of the SI. Other gaps in the SI literature remain. Although some investigators are examining alternate SI multiplier values, at this point, no research has been published.

Future studies are needed to test the effect of reducing SI risk category on incident hand-arm symptoms and disorders. For multi-task jobs, altering job rotation schedules could be explored as well as workstation or task design modifications.

In the current study it was not possible to explore alternate dose-response models for the separate measures variables. This is an area that could be addressed in future research using a larger sample.

In addition to future research, future software development could be another way to make the use of multi-task SI computation methods such as the CSI more accessible for practitioners. Until software becomes available for the multi-task CSI computation method, widespread use of the method is unlikely because manual calculation of more than a few SI scores may be too time consuming.

3.5. Conclusion

Evidence of associations between incident hand-arm symptoms and biomechanical exposures favored the use of the SI Model to the Separate Measures Model. Due to several sources of non-differential error inherent to the SI, estimations of risk presented in this paper were likely attenuated. If validated in an intervention study, we anticipate that work-related incidents of hand-arm symptoms can be prevented among manufacturing workers by modifying single- or multi-task jobs with SI scores > 9.

In addition to SI, percent duration of forceful exertions using SI methods appears to be another useful, predictive exposure metric for assessing multi-task jobs. In contrast, the specific exposure metrics used to assess exposure to forceful exertions and hand-wrist posture did not predict hand-arm symptoms in this sample.

Table 3.1. Exposure assessment methods and variables used to quantify exposures to biomechanical risk factors

Risk factor construct(s)	Method of Measurement	Exposure Variable (s)	Data type
Forceful exertion	EMG	Forearm extensor muscle (%RVE)* Forearm flexor muscle (%RVE)*	Continuous
	Qualitative Strain Index rating methods	Intensity of Exertion SI task parameter	5 ordinal categories
Repetition	Hand Activity Level	Hand Activity Level rating	Continuous
	Time-study	Percent duration of forceful exertions (%)	Continuous
		Rate of forceful exertions (exertions/ min)	Continuous
	Quantitative Strain Index rating methods	Duration of exertion SI task parameter	5 ordinal categories
		Efforts per minute SI task parameter	5 ordinal categories
	Qualitative Strain Index rating methods	Speed of work SI task parameter	3 ordinal categories
Non-neutral wrist posture	Multi-Video Task Analysis	Percent time wrist extension > 30° (%) Percent time wrist flexion > 30° (%)	Continuous
	Qualitative Strain Index rating methods	Hand-wrist posture SI task parameter	4 ordinal categories
Several biomechanical risk factors combined	Cumulative Strain Index computation method & Empirical SI classification method	Empirical SI risk category	4 ordinal categories

* Mean, task-specific %RVE values were selected as the exposure metric for time independent exposures; weekly peak mean %RVE values among all tasks performed in a given week were selected as the exposure metric for time-varying, weekly exposures.

Table 3.2. Descriptive statistics for biomechanical exposure variables by participant by task

Biomechanical exposure measures	Distribution of tasks N	(%)	Mean (SD)
Forceful exertions			
Mean forearm extensor muscle (% RVE)	959	--	54.2 (28.5)
Mean forearm flexor muscle (% RVE)	908	--	104.1 (88.0)
Intensity of Exertion SI rating criterion			
Light	350	(34%)	--
Somewhat Hard	566	(56%)	--
Hard	85	(8%)	--
Very Hard	15	(2%)	--
Near Maximal	4	(0%)	--
Repetition			
Hand Activity Level	957	--	5.0 (1.3)
Percent duration of forceful exertions (%)	1020	--	37.2 (16.0)
Duration of exertion SI rating criterion (%)			
< 10	42	(4%)	--
10-29	298	(29%)	--
30-49	489	(48%)	--
50-79	185	(18%)	--
≥ 80	6	(1%)	--
Rate of forceful exertions (exertions/ min)	1020	--	14.4 (7.0)
Efforts per minute SI rating criterion			
< 4	42	(4%)	--
4-8	158	(15%)	--
9-14	366	(36%)	--
15-19	303	(30%)	--
≥ 20	151	(15%)	--

SI = Strain Index

Table 3.2. continued

Biomechanical exposure measures	Distribution of tasks N (%)		Mean (SD)	
Speed of work SI rating criterion				
Very Slow/Slow/Fair	946	(93%)	--	
Fast	74	(7%)	--	
Very fast	0	(0%)	--	
Non-neutral wrist posture				
Percent time wrist extension (%)	958	--	10.0	(9.4)
Percent time wrist flexion (%)	958	--	3.4	(4.2)
Hand-wrist Posture SI rating criterion				
Very Good/Good	371	(36%)	--	
Fair	486	(48%)	--	
Bad	133	(13%)	--	
Very Bad	30	(3%)	--	

SI = Strain Index

Table 3.3. Descriptive statistics for weekly biomechanical exposures by hand-arm symptom status (N = 8735 symptom negative participant weeks; N = 92 symptom positive participant weeks)

		Hand-arm symptom status			
		Negative		Positive	
Biomechanical risk factor(s)	Weekly exposure measure	Mean (SD)	N (%)	Mean (SD)	N (%)
Forceful exertions:	Peak mean task forearm extensor muscle activity (% RVE)	61.5 (33.1)		66.5 (36.7)	
	Peak mean task forearm flexor muscle activity (% RVE)	124.9 (98.9)		127.5 (113.3)	
Repetition:	TWA Hand Activity Level	4.5 (1.4)		4.7 (1.1)	
	Percent duration of forceful exertions (%)	34.3 (14.0)		37.0 (12.9)	
	Rate of forceful exertions (exertions/min)	13.9 (6.2)		13.3 (5.2)	
Non-neutral wrist posture:	TWA percent time in wrist extension > 30°	8.8 (7.2)		10.2 (8.4)	
	TWA percent time in wrist flexion > 30°	2.9 (2.9)		2.5 (2.4)	
Several risk factors combined:	Peak daily SI score*	16.8 (14.3)		16.1 (14.3)	
	SI risk category**				
	Category 1		2907 (33%)		25 (27%)
	Category 2		1405 (16%)		17 (19%)
	Category 3		1849 (21%)		26 (28%)
	Category 4		2568 (30%)		24 (26%)

TWA = time-weighted average; SI = Strain Index; *SI score was calculated using the Cumulative Strain Index computation method for multi-task jobs; **The Empirical SI classification method introduced in Chapter 2 was used to assign SI risk category

Table 3.4. Pearson correlation coefficients (*r*) for associations between three weekly measures of hand repetition: percent duration of forceful hand exertions, rate of forceful exertions per minute, and time-weighted average Hand Activity Level.

Measure	Hand Activity Level	Percent duration of exertion
Percent duration of exertion	0.23	--
Rate of forceful exertions	0.12	0.47

Note: all Pearson correlation coefficients were statistically significant, $p < .001$

Table 3.5. Unadjusted associations between hand-arm symptoms and biomechanical exposure measures (Number of symptom negative participant weeks = 8735; Number of symptom positive participant weeks = 92)

Biomechanical exposure measure	Crude HR	Probability
Forceful exertions		
Forearm extensor muscle (% RVE)	1.00	0.14
Forearm flexor muscle (% RVE)	1.00	0.79
Repetition		
Hand Activity Level	1.08	0.33
Percent duration of exertions	1.01	0.13
Rate of forceful exertions (exertions/min)	0.99	0.47
Non-neutral wrist posture		
Percent time wrist extension	1.01	0.30
Percent time wrist flexion	0.96	0.26
Strain Index		
SI risk category		
Category 1	1.00	--
Category 2	1.69	0.10
Category 3	1.71	0.05
Category 4	1.17	0.59

Table 3.6. Final multivariable models of association between hand-arm symptoms and Strain Index (SI) exposure measures (Number of symptom negative participant weeks = 8735; Number of symptom positive participant weeks = 92)

Biomechanical model	HR	95% CI	p	AIC difference
Separate Measures Model				95.463
Forearm extensor muscle (% RVE)	1.01	1.00-1.01	0.24	
Forearm flexor muscle (% RVE)	1.00	1.00-1.00	0.24	
Hand Activity Level	1.01	0.84-1.22	0.90	
Percent duration of exertions	1.02	1.00-1.04	0.03	
Rate of forceful exertions (exertions/min)	0.98	0.94-1.03	0.43	
Percent time wrist extension	1.02	0.99-1.04	0.29	
Percent time wrist flexion	0.97	0.89-1.06	0.50	
SI Model				97.165
SI risk category				
Category 1	1.00	--	--	
Category 2	1.59	0.83-3.04	0.16	
Category 3	2.23	1.27-3.94	< 0.01	
Category 4	1.36	0.76-2.44	0.31	

Associations between biomechanical risk factors in the Separate Measures Model and hand-arm symptoms controlled for the seven biomechanical risk factors listed in table as well as sex, history of hand symptoms, weekly stress level, weekly job change, second job, and hand intensive non-work activity.

Associations between hand-arm symptoms and SI risk category controlled for the same covariates listed previously for the Separate Measures Model.

AIC difference for the Separate Measures Model = the absolute difference between the AIC value for the Separate Measures Model (829.046) and the AIC value for a multivariable model that included only the seven biomechanical risk factors (924.509) in the model (no confounders).

AIC difference for the SI Model = the absolute difference between the AIC value for the SI Model (834.766) and the AIC value for the unadjusted model of SI risk category (931.931).

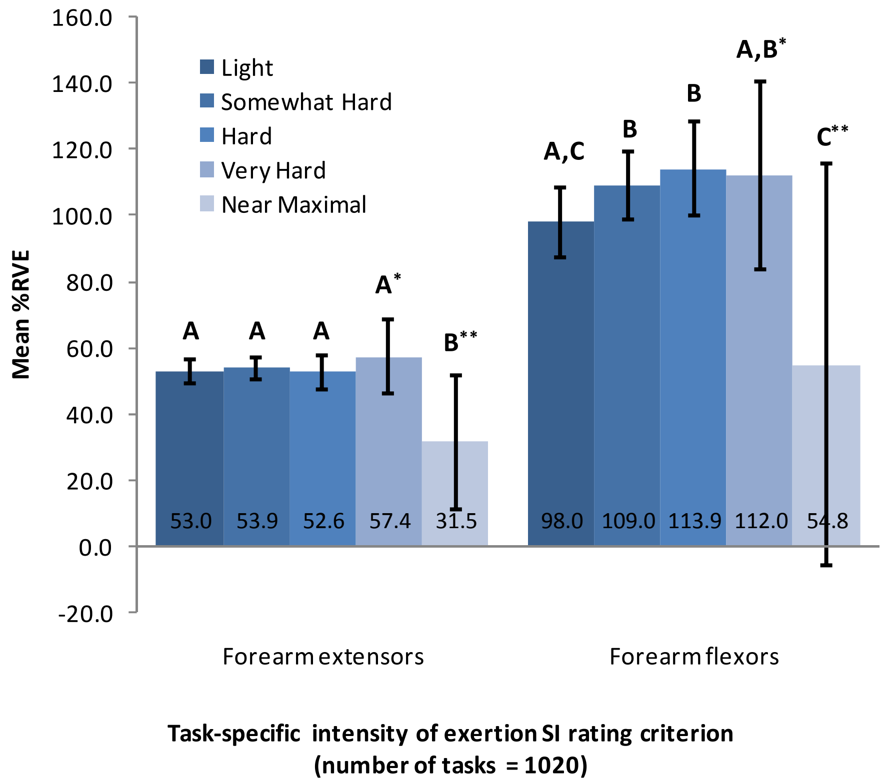


Figure 3.1. Least squares means and 95% CIs of forearm extensor and forearm flexor muscle activity measures (%RVE) (a) for task-specific least squares mean estimates by SI intensity of exertion task parameter rating criterion and (b) for weekly, peak mean task-specific estimates by SI risk category. For pairwise comparisons, differences in least squares mean estimates for categories with the same letter (A, B, C, or D) were not statistically significantly different ($\alpha > 0.05$). Error bars represent 95% CI.

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*Number of tasks = 15 for the Very Hard intensity of exertion rating criterion. **Number of tasks = 4 for the Near Maximal intensity of exertion rating criterion. General linear mixed-effect models for repeated measures were used to conduct pairwise comparisons.

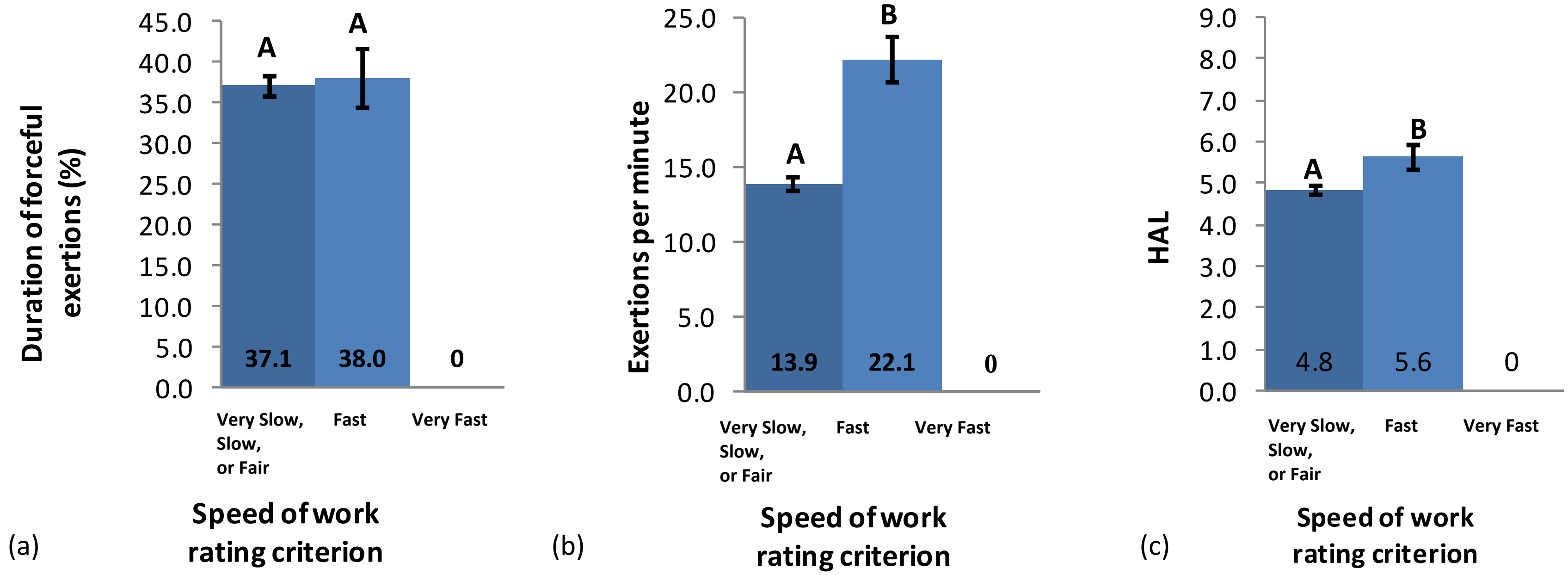

Figure 3.2. Least squares means and 95% CIs of task-specific estimates for three hand repetition exposure measures by SI task parameter rating criterion for speed of work: (a) percent duration of forceful hand exertions (b) rate of forceful exertions per minute, and (c) Hand Activity Level. For pairwise comparisons, speed of work rating criterion with the same letter (A or B) were not statistically significantly different ($\alpha = 0\ .05$). Error bars represent 95% CI.

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[*]Number of tasks = 4 for the Near Maximal intensity of exertion rating criterion. General linear mixed-effect models for repeated measures were used to conduct pairwise comparisons.

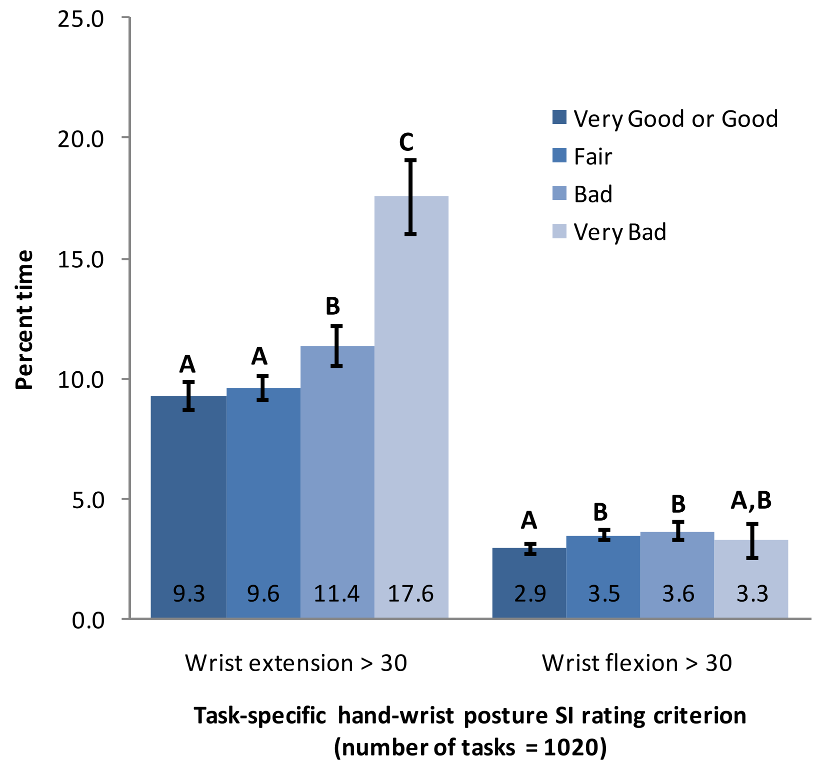

Figure 3.3. Least squares means and 95% CIs for non-neutral wrist posture exposure measures for percent time spent in wrist extension > 30° and wrist flexion > 30° for task-specific estimates by SI hand-wrist posture task parameter rating criterion and. For pairwise comparisons, differences in least squares mean estimates for categories with the same letter (A, B, C, or D) were not statistically significantly different ($\alpha = 0$ .05). Error bars represent 95% CI.

General linear mixed-effect models for repeated measures were used to conduct pairwise comparisons

CHAPTER 4. EFFECT OF CONCRETE BLOCK WEIGHT AND WALL HEIGHT ON LOW BACK BIOMECHANICS AMONG BRICKLAYERS: A LABORATORY STUDY

4.1. Introduction

Work-related low back disorders (LBDs) are common among construction workers and result in pain, disability, and substantial cost to workers and employers (Bureau of Labor Statistics, 2002; National Institute of Arthritis and Musculoskeletal and Skin Diseases (NIAMS), 2007). Among construction specialty trades, masonry workers have higher incidence rates (IR) of LBDs (IR = 31.1 per 100 person years) compared to all construction workers (IR = 22.2) (Bureau of Labor Statistics, 2007; The Center for Construction Research and Training, 2007). Masonry workers may experience high rates of LBDs because they work with awkward back postures and lift heavy materials (Engholm & Holmström, 2005; Everett, 1999; Hartmann & Fleischer, 2005; Jørgensen et al., 1991; Latza et al., 2000; van der Molen, Veenstra et al., 2004)

Although many masonry tasks have not changed over several centuries (Anton et al., 2005), recent interventions have been designed to reduce heavy lifting. One such intervention is the substitution of heavy building materials (*e.g.,* Concrete Masonry Unit (CMU) block) with lighter weight alternatives, *e.g.,* light-weight CMU block (LWB). Three recent studies evaluated the effect of lighter weight building materials on risk factor exposure magnitude among masons (Anton et al., 2005; van Der Molen et al., 2008; Zellers & Simonton, 1997). Two were controlled laboratory studies to evaluate the effect of substituting LWB for heavier CMU block on risk factor exposure levels among bricklayers (Anton et al., 2005; Zellers & Simonton, 1997).

Zellers and Simonton compared handling a traditionally shaped (two closed-end cores) CMU block to handling an “A” shaped (one closed-end core and one opened-end core) LWB. The investigators found that estimated low back disc compression forces decreased with the LWB but there were no differences for back postures, lumbar kinematics, LBD high-risk group membership probability (LBD risk probability) (Marras & Allread, 2006; Marras et al., 1993), back muscle activity, and heart rate.

Anton *et al.* (2005) conducted a laboratory study using LWB to examine the effects on back muscle activity and heart rate measures in which they compared LWB block to CMU blocks that were both traditionally shaped but different weights. Anton *et al.* (2005) observed reduced low back muscle activity for LWB in comparison to standard CMU block (SWB) at higher courses (rows). The researchers, however, did not evaluate back posture, lumbar kinematics, or LBD risk probability.

The purpose of the present laboratory simulation study was to quantify the effect of concrete block weight and wall height on: 1) back posture, 2) lumbar kinematics, 3) LBD risk probability, and 4) back muscle activity. Our first hypothesis was that, compared to SWB, laying LWB would be associated with more favourable exposures among all exposure metrics.Our second hypothesis was that, compared to ankle height (Course 1) or chest height (Course 7), laying block at knuckle height (Course 4) would be associated with lower (more favourable) exposure measures among metrics used to characterize sagittal flexion, lateral and twisting postures, back kinematics, sagittal moment, and LBD risk probability.

4.2. Research Design and Methods

4.2.1. Study Sample

Bricklayers between 21 and 60 years of age (including second through fourth year apprentices) were eligible to participate in the study. Bricklayers with a history of lumbar disc disorders, lumbosacral surgery, or cardiovascular disease were ineligible for participation. The Institutional Review Board at the University of Iowa approved this study and participants were compensated for their time.

4.2.2. Data Collection Instruments

4.2.2.1. Lumbar Motion Monitor

A Lumbar Motion Monitor (LMM), a portable triaxial electrogoniometer, was used to measure kinematics of the thoracolumbar spine. Data were transmitted to a desktop computer using an XStream-PKG radio modem (MaxStream, Orem, UT) and were sampled at 60 Hz via an analog-to-digital converter. The LMM was placed on the participant using a shoulder harness and waist belt in accordance with standard procedures (Marras et al., 1999; Marras et al., 1993). After placing the LMM, the participant was instructed to stand up straight without moving and resting spinal positions were measured in degrees.

4.2.2.2. LBD Risk Model

LBD risk probabilities were calculated using the *LBD risk model* developed by Marras *et al.* (1993). The LBD risk model is a reliable, predictive model for estimating the probability of being in a “high-risk” group for developing a work-related LBD (an incidence rate of 12 LBD per 100 full-time workers) for repetitive manual material handling tasks. Probability of “high-risk” group membership is classified as “high”, “medium”, or “low” based on cut-points for LBD risk probabilities (“high” = ≥ 70%; “medium” = 30% - 70%; “low” = < 30%) (Marras, Allread, Burr, & Fathallah, 2000). The model incorporates five variables, three of which were measured with the LMM (maximum sagittal flexion, average twisting velocity, maximum lateral velocity). The fourth variable, lifting rate, was calculated by dividing number of blocks lifted by the task duration (hr). The fifth variable, maximum static sagittal moment, is the product of block weight and moment arm length. For the current study, block weight was constant (LWB = 12.7 kg, SWB = 17.3 kg) and we assumed that moment arm lengths did not vary by wall height or block weight. Using standard procedures (Marras & Allread, 2006), sagittal moment arm lengths were measured at the lift origin and lift destination once per course . Consequently, differences in maximum sagittal moment by course for LWB compared to SWB were due solely to differences in block weight.

4.2.2.3. Surface Electromyography (EMG)

Surface electromyographic (EMG) recordings of the bilateral upper trapezius and bilateral lumbar erector spinae were used to estimate muscle activity level using standard electrode locations (Cram, Kasman, & Holtz, 1998; Jensen, Vasseljen, & Westgaard, 1993). Upper trapezius muscles were measured because they can be used to identify exposure to forceful exertions (Sporrong, Sandsjö, Kadefors, & Herberts, 1999) or shoulder abduction (Neumann, 2002), two risk factors that have been associated with an increased risk for developing rotator cuff tendonitis or other shoulder disorders (Frost et al., 2002; B. A. Silverstein et al., 2008). The surface EMG electrodes consisted of two 8 mm silver-silver chloride disks encased in 33x10 mm plastic housings with an interelectrode distance of 22 mm. On-site differential preamplification with a gain of 35 was used to minimize motion artifact (EQ, Inc., Chalfont, PA). A reference electrode was positioned over the non-dominant clavicle.

The electrodes were connected to a data logger system consisting of a microprocessor and 12-bit analog-to-digital converter unit (Tattletale_v2, Onset Computer Corp., Pocasset, MA); a custom EMG instrumentation board; and a compact-flash data storage unit (PERCF2V2I, Persistor Instruments, Inc., Bourne, MA). On the instrumentation board, the preamplified EMG signals were further amplified with a gain of 2000, bandpass filtered between 10 and 4000 Hz, and real-time root-mean-square (RMS) processed with a 100 ms time constant. The common-mode rejection ratio of the instrumentation system was 87 dB at 60 Hz. The RMS-processed signals were sampled at 100 Hz and the data stream from each channel was stored on the data logger's compact flash unit. Another 12-bit USB-based analog-to-digital converter (PMD-1208LS, Measurement Computing Co., Norton, MA) was used to monitor EMG signal quality during calibration and normalization procedures. The data logger was small enough (0.4 cm x 8.5 cm x 5.5 cm) to fasten to the front of the LMM harness and did not interfere with work tasks.

For each participant, erector spinae and upper trapezius EMG amplitudes were normalized separately to submaximal reference contractions using a standard load and expressed as percent relative voluntary effort (%RVE) (Mathiassen, Winkel, & Hägg, 1995). The procedures for erector spinae and upper trapezius normalization have been described previously (Anton et al., 2005). All EMG data were acquired and processed using custom EMG software (Fethke, Anton, Fuller, & Cook, 2004) developed in LabVIEW® (Version 7.1, National Instruments, Austin, TX).

4.2.2.4. Video Equipment

A digital video camera was positioned approximately 5 m from the experimental setup to minimize parallax errors and obstructed views. Researchers observed video recordings to: 1) synchronize LMM and EMG samples, 2) assist with extraction of discrete EMG samples, and 3) examine the validity of extreme values. These procedures are described in Section 2.4.

4.2.3. Experimental Setup and Procedures

Participants built two walls in a counterbalanced order, one with LWB and one with SWB. The procedures for wall construction have been described previously (Anton et al. 2005). All of the concrete blocks were of the same size and shape (32 whole blocks = 20.3 cm x 20.3 cm x 40.6 cm, 6 half blocks = 20.3 cm x 20.3 cm x 20.3 cm), differing only in weight, and came from one manufacturer (King's Material Inc., Coralville, IA). A masonry labourer maintained supply materials (block and mortar) on a 61 cm surface behind the bricklayer throughout the experiment (Figure 4.1). Participants were instructed to build the two walls at their normal work pace. A lighting system was used to synchronize LMM, EMG, and video data with the start and finish of a course. Consistent with good masonry practice, participants scraped excess mortar from the front of the wall. However, unlike building a wall in the field, no mortar was placed on the sides of the block. All participants rested twenty minutes before constructing the second wall to minimize the effects of fatigue on EMG measures.

4.2.4. Data Extraction and Processing

4.2.5. Statistical Analyses

Univariate analyses and tests of assumptions of normality were conducted for all exposure metrics. For all measures, normality was approximately satisfied.

For each of the 17 exposure metrics, a separate general linear mixed-effect model for repeated measures was used to quantify the fixed effects of block type and wall height. Block was a within-subjects factor with two fixed levels: LWB and SWB. Course was a within-subjects factor with seven fixed levels: Course 1 – Course 7. The interaction between course and block was a fixed factor, and subjects were a repeated, random factor. For the eight exposure metrics with significant interaction ($p < .10$) (Table 4.4.), the interaction term was kept in the model for all analyses. However, for the nine exposure metrics without significant interaction, a main effects only model was used. Overall, homogenous or heterogeneous Toeplitz variance/covariance structures were the best fit (smallest Akaike information criterion (AIC) values). The more parsimonious TOEP structure was preferred unless TOEPH yielded much smaller AIC values.

Comparisons were conducted to test the hypothesis that compared to SWB, laying LWB would be associated with more favourable exposures among all exposure metrics. Arithmetic means were used to test for the effect of block: 1) by wall (7 courses pooled); and 2) separately by Course 1, Course 4, and Course 7. Least squares means were used for between course comparisons for Course 1 vs. Course 4 and Course 7 vs. Course 4.

Comparisons were conducted to test the hypothesis that laying Course 4 block would be associated with lower (more favourable) exposure values for the 90th percentile lateral and twisting positions, mean twisting velocity, maximum lateral velocity, maximum static sagittal moment, and LBD risk probability when compared to laying Course 1 or Course 7 block. In the presence of significant interaction between course and block, comparisons were conducted separately for LWB and SWB. In the absence of significant interaction, comparisons were conducted using pooled (LWB and SWB) means.

All statistical analyses were performed using SAS version 9.2 (SAS Institute, Inc., Cary, NC).

4.3. Results

Twenty-five male bricklayers agreed to participate in the study. Demographic and personal data are in Table 4.1. Instrumentation and other errors resulted in a small amount of missing data for a few participants: all LMM data ($n = 1$); LMM data for one course ($n = 3$); all EMG data ($n = 3$); dominant erector spinae EMG data only ($n = 3$); non-dominant erector spinae ($n = 1$). Five instances of transient, artifact signals in the raw LMM time series data were corrected, as described in Section 2.4.

4.3.1. Overall Effect of Block Weight

Descriptive statistics of back posture, lumbar kinematics, lifting rate, LBD risk probability, and back muscle activity measures by block weight, wall, and course (limited to courses 1, 4, and 7) are presented in Table 4.2. Maximum sagittal moment for LWB was 29.9 Nm ($SD = 6.2$) compared to 40.7 Nm ($SD = 8.50$) for SWB ($p < .001$). Maximum sagittal moment is a function of block weight; therefore, these relatively large block weight effects were expected. Among the remaining exposure measures, four statistically significant, though relatively small, block weight effects were observed. Specifically, for LWB compared to SWB, 6.4% less time was spent in sagittal flexion > 30°($p < .05$), non-dominant side 90th percentile twisting angle increased by 12.7%, relative LBD risk probability improved by 5.8%, and non-dominant upper trapezius muscle activity improved by 8% ($p < .001$). Our hypothesis that compared to SWB, laying LWB would be associated with more favourable exposures among all exposure metrics was not supported by the evidence.

4.3.2. Effect of Block Weight at Specific Courses

The effect of block weight on back posture and muscle activity metrics varied significantly by course for the LWB compared to the SWB (Table 4.2). For example, for Courses 1, 4, and 7, significantly less time was spent in sagittal flexion > 30° while laying LWB compared to SWB (Course $1_{\text{LWB vs. SWB}}$ = 80.5% vs. 84.6%, $p < .01$; Course $4_{\text{LWB vs. SWB}}$ = 20.3% vs. 26.2%, $p < .05$; Course $7_{\text{LWB vs. SWB}}$ = 3.4% vs. 4.9%, $p < .05$). However, for percent time spent in sagittal flexion > 60° a block weight effect was seen only for Course 1 (Course $1_{\text{LWB vs. SWB}}$ = 45.6% vs. 50.6%, $p < .01$). A block weight effect was observed for non-dominant upper trapezius muscle activity for Course 4 but not for Course 1 or 7 (Course $4_{\text{LWB vs. SWB}}$ = 30.1 vs. 35.4, $p < .001$). Finally, a block weight effect was observed for non-dominant erector spinae muscle activity only for Course 7 ($p < .001$).

4.3.3. Effect of Course - Comparisons between Courses 1, 4, and 7

Overall, a statistically significant effect of course was observed on the four sagittal flexion variables, non-dominant 90th percentile lateral position, average twisting and maximum lateral velocity, lift rate, maximum sagittal moment, LBD risk probability, non-dominant erector spinae muscle activity, and bilateral upper trapezius muscle activity ($p < .01$) (Table 4.2).

4.3.3.1. Sagittal Flexion

A monotonic decrease was observed across Course 1, Course 4, and Course 7 in percent time spent in sagittal flexion > 30°, 90^{th} percentile sagittal flexion angle, and maximum sagittal flexion angle (Table 4.2.). The largest improvement in sagittal flexion metrics occurred between Course 1 and Course 4 (Tables 4.3, 4.4).

4.3.3.2. Lateral and Twisting Postures

Lateral and twisting posture measures were smaller for Course 4 versus Course 7, and similar between Courses 1 and 4 (Tables 4.3, 4.4). For example, for non-dominant 90^{th} percentile lateral position a 7.0° (*SE* = 0.7°) ($p < .001$) increase was observed for Course 7_{pooled} vs. Course 4_{pooled} but only a 0.1° (*SE* = 0.7°) ($p = .83$) increase was observed for Course 1_{pooled} vs. Course 4_{pooled}.

4.3.3.3. Trunk Velocity

A monotonic increase in velocity across Course 1_{pooled}, Course 4_{pooled}, and Course 7_{pooled} was observed for least squares mean twisting and maximum lateral velocity measures (Table 4.2.). From Course 1_{pooled} to Course 4_{pooled} the 1.7°/s increase in average twisting velocity was statistically significant ($p < .001$), but the 2.4°/s increase in maximum lateral velocity was not statistically significant (Table 4.3.). When Course 7_{pooled} was compared to Course 4_{pooled}, differences in average twisting velocity (difference = 1.5°/s) and in least squares mean maximum lateral velocity (difference = 11.8°/s) were statistically significant ($p < 0.001$) (Table 4.3.).

4.3.3.4. Lifting Rate

The effect of course on lifting rate was greatest when LWB was used (Table 4.4). Lifting rates were lowest for Course 4_{LWB} when compared to Course 1_{LWB} and Course 7_{LWB} (25.4 lifts/hour lower and 11.4 lifts/hour lower). The effect of course on lifting rates was smaller for SWB and not statistically significant.

4.3.3.5. Maximum Sagittal Moment

Small, statistically significant decreases in least squares mean maximum sagittal moment measures were observed for Course 1 vs. Course 4 and Course 7 vs. Course 4, which supported our hypothesis (Table 4.4.). For example, a 3.6 Nm (SE = 1.2) decrease was observed for Course 1_{SWB} vs. Course 4_{SWB} ($p < 0.01$), and a 5.8 Nm (SE = 1.3) decrease was observed for Course 7_{SWB} vs. Course 4_{SWB} ($p < .001$) (Table 4.4.).

4.3.3.6. LBD Risk Probability

A monotonic increase in least squares mean LBD risk probabilities across Course 1_{pooled}, Course 4_{pooled}, and Course 7_{pooled} was observed, but the only statistically significant difference was an 6.3% increased probability observed for Course 7_{pooled} vs. Course 4_{pooled} ($p < .001$) (Table 4.3.).

4.3.3.7. Back Muscle Activity

Dominant erector spinae muscle activity was significantly lower for Course 4_{SWB} compared to Course 1_{SWB} or Course 7_{SWB} ($\text{difference}_{\text{Course 1 vs. Course 4 SWB}}$ = -16.1 %RVE, SE = 5.5 %RVE, $p < 0.01$; $\text{difference}_{\text{Course 7 vs. Course 4 SWB}}$ = -11.6 %RVE, SE = 5.6 %RVE, p =0.04) (Table 4.4.). A similar effect was not observed for LWB. Dominant upper trapezius muscle activity measures were lower for Course 4_{pooled} compared to Course 7_{pooled} ($\text{difference}_{pooled}$ = 98 %RVE, $p < .001$), but measures for Course 1_{pooled} and Course 4_{pooled} were similar ($\text{difference}_{pooled}$ = 7 %RVE, p = .34) (Table 4.3.). Lastly, a statistically significant monotonic increase in least squares mean non-dominant upper trapezius muscle activity was observed across Courses 1_{pooled}, 4_{pooled}, and 7_{pooled} with the largest changes from Courses 4 to 7 (difference_{LWB} = 69.4 %RVE, difference_{SWB} = 66.8 %RVE, $p < .001$) (Table 4.4.).

4.4. Discussion

When building a seven course block wall, LWB exposure values were significantly lower than those observed for SWB for the following measures: percent time spent in sagittal flexion >30°, lifting rate, LBD risk probability (%), and non-dominant upper trapezius muscle activity. No block weight effect was observed among the twelve remaining exposure measures. It is not known whether the relatively small reductions in exposure associated with LWB would reduce the incidence of LBDs among masons.

For bricklayers, it appears that the differences in work height observed in this study had a greater influence on exposure to LBD risk factors than the 4.6 kg difference in block weight. Among all 17 exposure measures examined in this study, at least one statistically significant pairwise comparison for Course 1 vs. Course 4 or Course 7 vs. Course 4 was observed. Although one specific course was not consistently associated with lower (*i.e.*, more desirable) exposure measures, there were clear disadvantages to laying block at Course 1 or Course 7 (Table 4.5).

4.4.1. LBD Risk Model

4.4.1.1. Effect of Block Weight on LBD Risk Probability

Low back disorder risk probability values were 6% lower when participants used LWB compared to SWB, an observation that is consistent with the literature (Zellers & Simonton, 1997). The difference in LBD risk probability is, in this case, due primarily to the effect of LWB on one of the five high-risk group membership probabilities averaged by the LBD risk model, *i.e.*, the maximum sagittal moment. Specifically, the maximum sagittal moment LBD risk probability was approximately doubled as a consequence of block weight alone. Differences in the LBD risk probabilities were virtually null for the other four LBD model probabilities (data not shown).

4.4.1.2. Effect of Work Height on LBD Risk Probability and Trunk Velocity

Monotonic increases observed in LBD risk probability values across Course 1_{pooled}, Course 4_{pooled}, and Course 7_{pooled} were unexpected. We hypothesized that the lowest LBD risk probability values would be observed for Course 4. Increases in mean maximum lateral velocity and mean twisting velocity had a substantial effect on increasing LBD risk probabilities for higher work heights. Despite differences in experimental setup between the current study and Zellers and Simonton(1997), increases in maximum lateral velocity and least squares mean twisting velocity were observed as course height increased in both studies. Zellers and Simonton (1997) attributed the pattern of increasing velocity by course to increases in vertical distance travelled between lift origin and destination. However, results from the current study do not support this explanation. In particular, in the current study, vertical distance travelled for Course 4 was zero and for Courses 1 and 7 vertical distance travelled was identical. Alternatively, a greater degree of total twisting or total lateral rotation (sum of the maximum angle of lateral or twisting position in each direction) may be associated with monotonic increases in trunk velocities about an axis.

4.4.1.3. Applications of the LBD Risk Model for Bricklaying

A “medium” risk (30% - 70% LBD risk probability) of belonging to a “high-risk” LBD group (Marras et al., 2000) was associated with handling SWB as well as LWB. The LBD risk model is commonly used across many trades, including construction. However, the model’s validity is most well established among manufacturing tasks because the back posture and kinematic exposure data used to develop the LBD risk model were collected among material handling tasks in manufacturing. Among manufacturing workers, mean maximum sagittal flexion angles of 17.9° in the “high-risk" group and 10.4° in the "low-risk" group (Marras et al., 1993) were lower compared to means of at least 40° observed in the current study. Due to relatively moderate exposure values among the manufacturing tasks measured by Marras *et al.* (1993), maximum sagittal flexion values above a threshold of 23° do not influence LBD risk probability. Therefore, using the LBD risk model to estimate risk for the bricklaying activity in the current study may result in lower risk assessments compared to relatively higher risks for bricklaying compared to: 1) the literature, 2) LBD incidence rates, or 3) ergonomic lifting guidelines (van Der Molen et al., 2008; Washington State Department of Labor and Industries (L&I), ; Zellers & Simonton, 1997).

For example, Zellers and Simonton (1997) reported "medium" risk of belonging to a "high-risk" LBD group when participants used 11.8 kg CMUs, and "high" risk when 15 kg CMUs were used. In contrast, in the current study the risk of belonging to a "high-risk" LBD group was considered "medium" when using LWB as well as SWB. The higher LBD risk probability values observed in the previous study (Zellers & Simonton, 1997), overall, and for the 15 kg CMUs in particular, may be related to differences in experimental setup between the two studies (*e.g.* height of supply block relative to wall height). Additionally, the LBD risk probability results from the current study and from Zellers and Simonton (1997) are not as compelling as those from a recent field study suggesting that bricklayers should not lay blocks weighing ≥ 11 kg (van Der Molen et al., 2008). Also in contrast to the moderate risk estimates in the current study, LWB and SWB exceed the Lifting Limit of 11.7 kg calculated using the Washington State Department of Labor and Industries Lifting Calculator (Bernard, 2009; Washington State Department of Labor and Industries (L&I), 2000).

4.4.2. Back Posture

As expected, working at Course 4 was associated with substantially improved sagittal flexion measures compared to Course 1. Also, participants spent almost no time in sagittal flexion > 60° at Course 4. Similarly, van der Molen *et al.* (2004) examined the effect of elevating supply materials in the field and found that about 7% of work time was spent in sagittal flexion > 60° over a 4.5 h period. Back posture guidelines from the WISHA Checklist for Work-Related Musculoskeletal Disorders classify work activities with sagittal flexion > 30° in the "caution zone" if duration is > 2 hrs per day (25% time), and in the "hazard zone" if duration is > 4 hrs per day (50% time) (Bernard, 2009; Washington State Department of Labor and Industries (L&I), 2000). Assuming that the sagittal flexion results from the current study were representative of a full work day, then "hazard zone" back posture classification would apply for bricklaying at ankle height (LWB and SWB) and at knuckle height for SWB. However, neither "hazard zone" or "caution zone" back posture classifications would apply for bricklaying conducted at chest height (LWB and SWB) and knuckle height using LWB. This assessment using the WISHA Checklist for Work-Related Musculoskeletal Disorders is consistent with other research that associates time spent in sagittal flexion >30° with LBD (Hoogendoorn et al., 2000; Lötters, Burdorf, Kuiper, & Miedema, 2003).

4.4.3. Lifting Rates

Lifting rates were slower for Course 4 compared to Course 1 or Course 7, which was unexpected. For this study, even numbered courses were built with six blocks (four whole blocks and two half blocks) and odd numbered courses were built with five whole blocks. According to an administrator from the Masonry Institute of Iowa, half block construction takes longer than whole block construction (R. Gunderson, personal communication, July 10, 2009). Compared to the brief block laying task performed for this study, half-blocks would have less of an influence on lifting rates over an entire workday, especially when building longer walls. The variability in lifting rates by course appears be a result of the experimental procedures in this study and would most likely not be observed in field conditions.

4.4.4. Lower and Upper Back Muscle Activity

4.4.4.1. Effect of Block Weight on Muscle Activity

LWB use was associated with lower muscle activity for the non-dominant upper trapezius, but had no effect on the dominant upper trapezius muscle activity nor on the bilateral erector spinae. Except for the non-dominant upper trapezius, these surface EMG results were consistent with the findings of Anton *et al.* (2005). Direct comparisons between Anton *et al.* (2005) and the current study are limited by substantial differences in EMG sampling procedures. Specifically, we analyzed EMG for the entire wall building activity while Anton *et al.* (2005) analyzed EMG for lifting and lowering for one block at three different courses (1, 3, and 7).

4.4.4.2. Effect of Work Height on Muscle Activity

The substantial increases in upper trapezius muscle activity at the highest course were expected and are consistent with the findings of Anton *et al.* (2005). In the current study, dominant upper trapezius muscle activity was over 300% greater at the highest course compared to work at knuckle height and 400% greater for the analogous locations reported by Anton *et al* (2005). Also, in the current study, non-dominant upper trapezius muscle activity was over 250% greater at the highest course compared to work at knuckle height, compared to 1300% reported by Anton *et al.* (2005) for the analogous locations. The larger differences observed by Anton *et al.* (2005) are most likely because the investigators evaluated Course 3 rather than Course 4. Unexpectedly, upper trapezius muscle activity was greater on the dominant side vs. non-dominant side in the current study whereas the opposite was observed by Anton *et al.* (2005). As previously noted, contrasting results between the two studies may be due to substantial differences in EMG sampling procedures.

In the literature, higher levels of upper trapezius muscle activity are inconsistently identified as a risk factor for musculoskeletal disorders (Bosch, De Looze, & Van Dieen, 2007; Hansson et al., 2000; Johnston, Jull, Darnell, Jimmieson, & Souvlis, 2008; Kallenberg, Hermens, & Vollenbroek-Hutten, 2006; Westgaard, Vasseljen, & Holte, 2001). If increased upper trapezius muscle activity is a risk factor, then, in the absence of other worksite modifications, exposure may be reduced if masons avoiding bricklaying at or above chest height.

4.4.5. Limitations

The findings of this study should be interpreted in light of differences between experimental conditions and actual fieldwork. Efforts were made to replicate fieldwork conditions for laying CMU block while controlling for sources of variability. The experimental setup was designed with the assistance of a journey-level masonry instructor to be as realistic as possible despite the laboratory setting. In order to isolate the effects of block weight and wall height, the supply height for mortar and block was fixed at 61 cm and participants were instructed to use two hands for all lifts. These conditions may not be found in actual field work.

While previous studies limited analyses to the block lifting activity, the current study sampled the entire block laying task (applying mortar, laying all blocks, fixing alignment, moving line block), which introduced more sources of variability. While this method made direct comparisons of our observations to others more difficult, it may be easier to generalize our observations to actual fieldwork.

Because it was not possible to measure sagittal moment arm length while the participants were working at their normal pace, sagittal moment arm length was measured at each course after constructing the wall. Therefore, moment arm measurements for this study may not represent field conditions and the maximum sagittal moment and LBD risk probability values calculated from them may not be representative of field conditions. However, moment arm length measurement error would not impact the effects we observed for block weight because we assumed that sagittal moment arm lengths by course did not vary across block weights.

Further research under field conditions is needed to examine the effects of LWB and wall height on back posture, lumbar kinematics, LBD risk probability, and back muscle activity exposure measures observed in this study. Also, further epidemiologic research should be conducted to examine the association between block weight and low back health outcomes among bricklayers rather than making inferences on the effect of LWB on LBD "high-risk" group probability as assigned by biomechanical models.

4.5. Conclusions

Substituting lighter weight building materials, such as LWB, appears to reduce exposure to several biomechanical risk factors for LBD among bricklayers. However, exposure to biomechanical risk factors for LBDs and other musculoskeletal disorders may remain high among masons, even if LWB were used exclusively (Spielholz, Davis, & Griffith, 2006). Even so, we recommend that, architects and designers consider the effect of block weight on workers' exposure to LBD risk factors when selecting construction materials.

Regarding work height, our results suggest that work conducted at ankle height and chest height were generally associated with higher exposure to risk factors than work performed at knuckle height. If validated in field studies, this suggests that bricklaying at heights between ankle height and chest height will reduce the risk of musculoskeletal disorders among bricklayers.

Figure 4.1. Experimental setup.

Table 4.1. Demographic, personal data

Characteristic	Mean	(*SD*)	N	(%)
Age (years)	30.9	(7.8)	--	--
Height (cm)	180.5	(5.7)	--	--
Weight (kg)	89.6	(14.5)	--	--
BMI (kg/cm^2)	27.5	(4.4)	--	--
Work experience (years)	8.8	(6.1)	--	--
2nd year apprentice	--	--	1	(4.0)
3rd year apprentice	--	--	3	(12.0)
4th year apprentice	--	--	4	(16.0)
Journeyman	--	--	17	(68.0)
Left handedness	--	--	2	(8.0)

Table 4.2. Measures by block, by course, and the effect of block weight and course for: back posture; back kinematics; LBD risk probability; muscle activity (%RVE) for dominant (Dom) and non-dominant (Ndom) upper trapezius and lumbar erector spinae.

			Mean (SD)							
Variable	n	Block	Wall		Course 1		Course 4		Course 7	
Sagittal flexion >30° (% time)†‡	24	LWB	37.8 [c]	(8.4)	80.5 [b]	(11.4)	20.3 [c]	(15.3)	3.5 [c]	(3.8)
		SWB	40.4	(11.2)	84.6	(9.5)	26.2	(20.7)	4.9	(4.2)
		LWB & SWB pooled	39.1	(9.9)	82.5	(10.5)	23.3	(18.2)	4.2	(3.9)
Sagittal flexion >60° (% time)†	24	LWB	16.9	(7.8)	45.6 [b]	(16.4)	2.6	(2.7)	1.4	(1.9)
		SWB	17.6	(8.8)	50.6	(12.5)	1.5	(1.0)	1.0	(0.0)
		LWB & SWB pooled	17.3	(8.2)	48.1	(14.6)	2.1	(2.1)	1.2	(1.4)
Maximum sagittal flexion*†	24	LWB	81.6	(12.0)	80.7	(12.4)	58.0	(15.6)	41.5	(16.5)
		SWB	82.2	(11.1)	81.6	(10.8)	55.4	(15.4)	46.4	(19.3)
		LWB & SWB pooled	81.9	(11.4)	81.1	(11.5)	56.7	(15.4)	44.0	(17.9)
90th percentile sagittal flexion (°)†‡	24	LWB	72.3	(11.2)	77.6	(12.1)	38.0	(12.1)	24.2	(8.1)
		SWB	72.8	(11.3)	79.1	(10.8)	37.9	(10.3)	24.5	(6.7)
		LWB & SWB pooled	72.6	(11.1)	78.4	(11.4)	37.9	(11.1)	24.4	(7.3)
Dom 90th percentile lateral position (°)‡	24	LWB	13.0	(3.3)	13.6	(5.4)	10.9	(2.9)	13.2	(4.0)
		SWB	13.4	(3.9)	13.3	(6.3)	11.7	(4.2)	13.0	(4.2)
		LWB & SWB pooled	13.2	(3.6)	13.5	(5.8)	11.3	(3.6)	13.1	(4.1)

LBD=low back disorder; *LBD risk model variable; †course effect statistically significant, $p < 0.01$; ‡ significant block and course interaction present, $p < 0.10$; LWB = light-weight block; SWB = standard-weight block; the effect of block weight: a $p < 0.001$; b $p < 0.01$; c $p < 0.05$; d $p \leq 0.10$.

Table 4.2. continued

Variable	n	Block	Mean (*SD*)							
			Wall		Course 1		Course 4		Course 7	
Ndom 90th percentile lateral position (°)†‡	24	LWB	11.7	(3.2)	8.6	(3.0)	8.5	(3.6)	15.2	(4.6)
		SWB	11.6	(2.5)	8.4	(3.2)	7.9	(2.9)	15.3	(3.2)
		LWB & SWB pooled	11.6	(2.8)	8.5	(3.0)	8.2	(3.2)	15.2	(3.9)
Dom 90th percentile twisting position (°)	24	LWB	8.5	(2.5)	7.4	(4.0)	7.4	(3.8)	9.0 [c]	(3.4)
		SWB	8.5	(3.1)	8.2	(4.3)	7.7	(3.3)	7.9	(3.3)
		LWB & SWB pooled	8.5	(2.8)	7.8	(4.1)	7.5	(3.5)	8.5	(3.4)
Ndom 90th percentile twisting position (°)‡	24	LWB	12.7 [a]	(4.1)	13.3	(5.2)	11.7 [c]	(5.3)	12.5	(4.3)
		SWB	11.8	(3.8)	12.3	(4.7)	10.4	(3.9)	12.3	(3.7)
		LWB & SWB pooled	12.3	(3.9)	12.8	(5.0)	11.0	(4.6)	12.4	(4.0)
Mean twisting velocity (°/s) *†‡	24	LWB	5.6	(1.9)	4.0	(1.5)	5.7	(1.9)	7.3	(2.8)
		SWB	5.6	(2.0)	4.0	(1.5)	5.7	(2.2)	7.1	(2.7)
		LWB & SWB pooled	5.6	(1.9)	4.0	(1.5)	5.7	(2.1)	7.2	(2.7)
Maximum lateral velocity (°/s) *†‡	24	LWB	71.6	(15.5)	51.5	(17.5)	53.1	(9.6)	65.2	(18.2)
		SWB	73.9	(17.2)	51.7	(14.0)	54.2	(7.7)	66.0	(15.7)
		LWB & SWB pooled	72.8	(16.3)	51.6	(15.7)	53.6	(8.6)	65.6	(16.8)

*low back disorder risk model variable; †course effect statistically significant, $p < 0.01$; ‡ significant block and course interaction present, $p < 0.10$; LWB = light-weight block; SWB = standard-weight block; the effect of block weight: [a] $p < 0.001$; [b] $p < 0.01$; [c] $p < 0.05$; [d] $p \leq 0.10$.

Table 4.2. continued

Variable	n	Block	Mean (SD) Wall		Course 1		Course 4		Course 7	
Lift rate (lifts/hour) *†	24	LWB	164.0 [a]	(32.6)	170.1	(32.4)	145.9	(36.5)	157.3	(37.8)
		SWB	165.0	(36.8)	161.2	(41.2)	154.2	(37.6)	152.0	(30.4)
		LWB & SWB pooled	164.5	(34.4)	165.6	(37.0)	150.0	(36.9)	154.6	(34.0)
Maximum sagittal moment (Nm) *†	24	LWB	29.9 [a]	(6.2)	28.6 [a]	(5.8)	25.9 [a]	(4.9)	30.0 [a]	(5.7)
		SWB	40.7	(8.5)	38.9	(7.9)	35.3	(6.7)	41.5	(7.3)
		LWB & SWB pooled	35.3	(9.2)	33.7	(8.6)	30.6	(7.5)	35.7	(8.7)
Low back disorder risk probability (%)†‡	24	LWB	54.9 [a]	(6.1)	47.0 [c]	(5.1)	48.5 [b]	(6.2)	55.1 [c]	(10.1)
		SWB	58.3	(5.2)	49.7	(6.8)	52.4	(5.8)	58.2	(7.8)
		LWB & SWB pooled	56.6	(5.8)	48.4	(6.1)	50.4	(6.2)	56.6	(9.0)

*low back disorder risk model variable; †course effect statistically significant, $p < 0.01$; ‡ significant block and course interaction present, $p < 0.10$; LWB = light-weight block; SWB = standard-weight block; the effect of block weight: [a] $p < 0.001$; [b] $p < 0.01$; [c] $p < 0.05$; [d] $p \leq 0.10$.

Table 4.2. continued

Variable	n	Block	Wall		Course 1		Course 4		Course 7	
			Mean (*SD*)							
Dom erector Spinae (%RVE)	19	LWB	65.4	(23.5)	65.3 [d]	(28.1)	71.3	(23.1)	63.9 [a]	(22.8)
		SWB	66.5	(24.3)	61.9	(24.5)	74.3	(26.1)	63.1	(20.6)
		LWB & SWB pooled	66.0	(23.9)	63.6	(26.1)	72.8	(24.4)	63.5	(21.4)
Ndom erector Spinae (%RVE)[†]	21	LWB	70.2	(24.4)	68.6	(24.4)	73.7	(16.8)	69.9 [a]	(22.1)
		SWB	73.0	(23.6)	68.6	(23.5)	72.1	(15.7)	79.2	(28.3)
		LWB & SWB pooled	71.6	(22.5)	68.6	(23.7)	72.9	(16.1)	74.5	(35.5)
Dom upper Trapezius (%RVE)[†‡]	22	LWB	81.8	(62.1)	49.7	(36.0)	55.9	(38.0)	152.9	(76.9)
		SWB	83.5	(71.7)	47.9	(40.8)	59.6	(42.8)	155.0	(97.7)
		LWB & SWB pooled	82.7	(66.9)	48.8	(38.0)	57.8	(40.1)	154.0	(86.9)
Ndom upper Trapezius (%RVE)[†]	22	LWB	46.0 [a]	(37.5)	17.5	(13.2)	30.1 [b]	(13.8)	100.3	(35.3)
		SWB	50.0	(38.2)	18.8	(14.4)	35.4	(15.0)	103.1	(26.9)
		LWB & SWB pooled	48.0	(37.9)	18.1	(13.7)	32.7	(14.5)	101.7	(31.1)

[*]low back disorder risk model variable; [†]course effect statistically significant, p <0.01; [‡] significant block and course interaction present, p <0.10; LWB = light-weight block; SWB = standard-weight block; the effect of block weight: [a] $p < 0.001$; [b] $p < 0.01$; [c] $p < 0.05$; [d] $p \leq 0.10$.

Table 4.3. Pairwise comparisons of least squares means for pooled LWB & SWB: Course 1 vs. Course 4 and Course 7 vs. Course 4 for: back position; back kinematics; low back disorder risk probability*; muscle activity (%RVE) for dominant (Dom) upper trapezius.

	Course 1 vs. Course 4			Course 7 vs. Course 4		
Variable	Estimate	SE	*p*	Estimate	SE	*p*
Sagittal flexion > 30° (% time)	60.9	2.3	<0.001	-17.8	2.3	<0.001
90th percentile sagittal flexion (°)	40.8	2.1	<0.001	-13.9	1.9	<0.001
Dom 90th percentile lateral position (°)	2.2	1.0	0.03	2.0	1.0	0.04
Ndom 90th percentile lateral position (°)	0.1	0.7	0.83	7.0	0.7	<0.001
Ndom 90th percentile twisting position (°)	1.9	0.7	0.01	1.4	0.7	0.06
Mean twisting velocity (°/s) *	-1.7	0.3	<0.001	1.5	0.4	<0.001
Maximum lateral velocity (°/s) *	-2.4	2.2	0.28	11.8	2.2	<0.001
Low back disorder risk probability (%)	-2.0	1.3	0.12	6.3	1.3	<0.001
Dom upper trapezius (%RVE)	-7.2	7.6	0.34	98.0	7.6	<0.001

Table 4.4. Pairwise comparisons of least squares means by block weight for Course 1 vs. Course 4 and Course 7 vs. Course 4 for: back position; back kinematics; muscle activity (%RVE) for dominant (Dom) and non-dominant (Ndom) lumbar erector spinae and Ndom upper trapezius.

		Course 1 vs. Course 4			Course 7 vs. Course 4		
Variable	Block weight	Estimate	SE	*p*	Estimate	SE	*p*
Sagittal flexion > 60° (% time)	LWB	43.2	3.5	<0.001	-1.0	3.5	0.77
	SWB	49.3	3.5	<0.001	0.0	3.5	0.99
Maximum sagittal flexion*	LWB	20.6	2.9	<0.001	-19.2	3.3	<0.001
	SWB	23.9	2.8	<0.001	-12.6	3.2	<0.001
Dom 90th percentile twisting position (°)	LWB	-0.7	0.8	0.41	1.7	0.6	0.01
	SWB	0.0	0.8	0.95	0.2	0.6	0.74
Lift rate (lifts/hour) *	LWB	25.4	5.3	<0.001	11.4	4.9	0.02
	SWB	9.0	5.3	0.09	-4.3	4.9	0.38
Maximum sagittal moment (Nm) *	LWB	2.8	1.2	0.02	3.6	1.3	0.01
	SWB	3.6	1.2	<0.01	5.8	1.3	<0.001
Dom erector spinae (%RVE)	LWB	-8.2	5.6	0.15	-9.0	5.5	0.11
	SWB	-16.1	5.5	<0.01	-11.6	5.6	0.04
Ndom erector spinae (%RVE)	LWB	-4.5	3.9	0.24	-6.8	4.1	0.10
	SWB	-4.2	3.9	0.29	5.5	4.1	0.18
Ndom upper trapezius (%RVE)	LWB	-12.8	3.5	<0.001	69.4	6.4	<0.001
	SWB	-16.0	3.7	<0.001	66.8	6.3	<0.001

Table 4.5. Summary of statistically significant ($\alpha < .05$) observed differences for laying block at ankle- (Course 1), knuckle- (Course 4), or chest-height (Course 7).

Variable	Most favorable work height	Least favorable work height
All four sagittal flexion metrics	Chest-height	Ankle-height
90th percentile Dom lateral position	Knuckle-height	--
90th percentile Ndom lateral position	--	Chest-height
90th percentile Dom twisting position	--	Chest-height
90th percentile Ndom twisting position	Knuckle-height	--
Mean twisting velocity	--	Chest-height
Maximum lateral velocity	Knuckle-height	Chest-height
Lifting rate (LWB only)	Knuckle-height	--
Maximum sagittal moment	Knuckle-height	--
LBD risk probability	--	Chest-height
Dom low back muscle activity (SWB only)	--	Knuckle-height
Ndom low back muscle activity	--	--
Dom upper trapezius muscle activity	--	Chest-height
Ndom upper trapezius muscle activity	Ankle-height	Chest-height

CHAPTER 5. CONCLUSIONS

5.1. Summary

Fundamentally, the goal of this dissertation was to provide empirical evidence useful for the prevention of MSDs. To this end, three studies were conducted. The first two studies were conducted to explore strategies for categorizing occupational risk of hand-arm symptoms among manufacturing workers and the third study was conducted to evaluate the effect of an intervention hypothesized to reduce exposure to LBD biomechanical risk factors among bricklayers.

Evidence presented in Chapters 2 and 3 may improve the ability of researchers and occupational health practitioners to prevent UEMSDs by providing empirical evidence that the Strain Index is a valid method of identifying hazardous jobs among manufacturing workers and targeting those jobs for exposure reduction. Despite some limitations, these efforts serve to improve the prevention of hand-arm symptoms resulting from exposure to forceful exertions, repetition, and non-neutral wrist postures by improving our understanding of a widely used exposure assessment tool.

For the study presented in Chapter 4 (LWB Intervention Study), a laboratory study of 25 bricklayers was conducted to estimate the effect of block weight and course height on LBD risk factor exposures. In Chapter 4 it was demonstrated that bricklayers' exposure to LBD risk factors can be reduced by handling LWB at heights between ankle and chest height.

5.2. Strain Index Study I

This study provides the first empirical evidence of association between SI risk category and incident hand-arm symptoms. The study provided several findings with practical implications for occupational health practitioners and researchers. Specifically, empirical evidence from Strain Index Study I provided support for a new set of cut-points that can be used to interpret SI results for multi-or single-task jobs. For years investigators and practitioners have argued that the Original SI classification cut-point values (3, 5, and 7) were too low to make meaningful distinctions between the degree of risk between tasks. Specifically, it was common in practice or research for most jobs to be categorized as Hazardous, which made it difficult to prioritize jobs for intervention.

In contrast, compared to the Original Structure, multivariable models of associations between Empirical Structure (established for this study) and incident hand-arm symptoms were a better fit to the data and provided evidence of association between higher strata SI risk categories compared to the referent category. Of particular interest were the results among female participants. All the Empirical categories were more predictive among women. Despite potentially unstable gender stratified risk estimates, compelling evidence in favor of the Empirical Structure was observed for this group of manufacturing workers. Furthermore, because of non-differential measurement error, it is likely that the observed associations between both Original and Empirical risk categories and incident hand-arm symptoms were attenuated compared to true associations. If the findings from this study are replicated, MSD prevention will be more effective when using the Empirical SI classification method.

5.3. Strain Index Study II

In Chapter 3, SI methods were compared to separate exposure assessment methods used to measure forceful exertions, repetition, and non-neutral wrist postures. Evidence of associations between incident hand-arm symptoms and biomechanical exposures favored the use of the SI Model over the Separate Measures Model. Although the overall Separate Measures Model was not very useful, the percent duration of forceful exertions exposure metric appeared to have some value. For every 1% increase in percent duration of forceful exertions, a 2% increase in risk of incident hand-arm symptoms was observed.

5.4. LWB Intervention Study

In Chapter 4, we quantified the effect of concrete block weight and wall height on: 1) back posture, 2) lumbar kinematics, 3) LBD risk probability, and 4) back muscle activity. Substituting lighter weight building materials for heavier materials, appears to reduce exposure to several biomechanical risk factors for LBD among bricklayers. It is not known whether the relatively small reductions in exposure associated with using LWB would affect the incidence of LBDs among bricklayers. Some investigators have suggested that exposure to biomechanical risk factors for LBDs and other musculoskeletal disorders may remain high among bricklayers even if LWB were used exclusively (Spielholz et al., 2006). Even so, we recommend that architects and designers consider the effect of block weight on workers' exposure to LBD risk factors when selecting construction materials.

Regarding work height, our results suggest that work conducted at ankle height and chest height was generally associated with higher exposure to LBD risk factors than work performed at knuckle height. If validated in field studies, this suggests that bricklaying at heights between ankle height and chest height would reduce exposure to LBD biomechanical risk factors among bricklayers.

5.5. Future Research

This dissertation addressed some of the gaps in the literature. Important knowledge gaps in the literature remain, however.

Chapters 2 and 3 of this dissertation aimed to address some of the gaps in the Strain Index literature. It may be possible to validate the findings from Strain Index Studies I & II through collaborations with other research teams. Specifically, the SI is being used by several other research teams as an exposure assessment method in prospective studies of upper extremity musculoskeletal symptoms.

Lessons learned from Strain Index Studies I & II suggest several areas of future research, including:

- Verifying the SI classification method results for Original, Empirical and *post hoc* Structures among other samples of manufacturing workers
- Examining whether results from this study for the Empirical or *post hoc* SI classification methods can be generalized to workers in other industries
- Examining whether the Empirical Structure can predict neck-shoulder symptoms among the Iowa Study participants
- Examining the effect of using alternate multi-exertion or multi-task SI computation methods on observed associations between Empirical risk categories and incident hand-arm symptoms or disorders
- Exploring alternate, more objective, methods of ascertaining SI task parameter rating criterion by using direct measures such as surface electromyography or electrogoniometry
- Validate the relative weights of the SI task parameter multipliers
- Conduct an intervention effectiveness study in a manufacturing environment to evaluate the effect of reducing SI scores and Empirical risk category measures on incident hand-arm symptoms
- Develop software for calculating multi-task SI scores with the CSI calculation method

Further research on the areas listed above should help improve the understanding of the SI and improve our ability to correctly identify high-risk jobs.

Chapter 4 of this dissertation aimed to address some of the gaps in the knowledge related to using LWB. The manuscript for Chapter 4 was submitted in September 2009 to the journal *Ergonomics*. Reviewer comments were received in January 2010 and we will revise and resubmit in the new few months. The LWB Intervention Study was sponsored by CPWR – the Center for Construction Research and Training (CPWR). Results from this study will be disseminated to stakeholders with the help of CPWR. Construction Solutions is an online database of occupational hazards and engineering interventions is being developed by CPWR. Results from this study should be incorporated in the 'Lightweight Concrete Block' Construction Solutions page: (http://www.cpwrconstructionsolutions.org/masonry/solution/48/lightweight-concrete-block.html).

Lessons learned from the LWB intervention study suggest areas of future research. For example:

- Conducting a field study to verify the effects of LWB and wall height on back posture, lumbar kinematics, LBD risk probability, and back muscle activity exposure measures observed in this study
- Conducting an epidemiologic research study to examine the association between block weight and musculoskeletal health outcomes among bricklayers

Further research in these areas would evaluate whether there is evidence of an association between the effect of block weight and health outcomes. We recommend including back and upper extremity health outcomes in future epidemiologic studies. Widespread adoption of LWB is dependent upon many factors.

APPENDIX A: GLOSSARY

Table A1. A glossary of terms used to describe work.

Word or phrase	Definition
cyclic	A task is considered cyclic if essentially the same series of *work elements* is repeated over the course of a rotation or an entire shift.
exertion	An exertion is a required hand/wrist motion that involves hand or forearm muscular effort during task performance, regardless of the force required (Bao et al., 2006a). An exertion is composed of a sequence of *MTM elements* (Fallentin et al., 2001).
forceful exertion	A forceful exertion is a required hand/wrist motion, action, or *work element* (*e.g.* using the hand to hold, manipulate, trigger, push, pull, or otherwise handle an *object*) that requires a non-negligible level of force (Kapellusch & Garg, personal communication, May 12, 2008). Alternate definition for forceful exertion (Stetson et al., 1991): a forceful hand exertions is "a conspicuous application of force by the hand and includes using the hand to hold, manipulate, trigger, push, pull, or otherwise handle an *object*."
job	Workers perform a job during a *shift*.
job rotation	Job rotation occurs when a worker performs two or more tasks per *shift*.
mono- task	Also referred to as 'single-exertion tasks', these tasks are comprised of one forceful exertion repeated for one rotation within a *shift*, or for an entire *shift* if it is a *mono-task job*.
multiple-exertion tasks	Task that are comprised of two or more *work elements*
mono-task job	A *mono-task* that is performed for the entire *shift*. By definition, a *mono-task job* is a sub-category of *single-task jobs*.
methods-time measurement (MTM) hand motions	MTM-1 hand motions include these elements: reach, move, turn, apply pressure, grasp, position, release, disengage (Konz, 2004) (*e.g.* reach to an object, move object to the other hand, move object to an approximate location, pickup grasp, re-grasp an object to improve control, release an object).
multiple-task job	A worker rotates between two or more tasks per *shift*.

Words or phrases in *italics* or defined elsewhere within Table A1.

Table A1. continued

non-cyclic	All non-cyclic tasks are also *multiple exertion tasks*. In this study there were two types of non-cyclic tasks. The first type of non-cyclic task is comprised of several *cyclic work elements*, but the work elements are not always performed in the same sequence or for the same duration. The second type of non-cyclic task is comprised of several *work elements* that are not repeated over the course of a rotation or an entire shift.
object	An object is "virtually anything with which the hand contacts, *e.g.*, a part, a tool, or a machine control button" (Bao et al, 2006).
shift	A shift is typically an 8-hour period of time in one day
single-exertion job	Refer to *mono-task job* definition
single-task job	One task is performed for an entire shift. In other words, there is no job rotation.
task	A task has a unique purpose (*e.g.* assembly basepan, braze basepan, secure lids onto the top of crates to prepare them for shipping, install gaskets on doors, program refrigerator water dispensers) and is an essential part of a person's job.
work element	A work element is a functional part of a task that is associated with one or more *exertions* (*e.g.* remove the clear film protective coating from a stainless steel refrigerator door, move a door from the conveyor and put it on a rack, plug the holes in a refrigerator liner, attach a skid to the basepan, etc.).

Words or phrases in *italics* or defined elsewhere within Table A1.

APPENDIX B: CATEGORIZING TASKS INTO HOMOGENOUS EXPOSURE GROUPS

B.1. Introduction

The SI was created to evaluate jobs, not people. In the literature there is some evidence that, even among homogenous task groups, individual variation in work-style results in considerable inter-individual exposure variability (Rappaport, Kromhout, & Symanski, 1993). During the Iowa Study, physical exposure and video data were collected for 886 individual tasks from among the 282 participants eligible for Strain Index Studies I & II. For the purposes of this dissertation, it was not feasible to conduct SI ratings among all 886 tasks. At this facility, many participants performed the same *task*. Therefore, it was decided that *if* it were possible to establish a reasonable number of *task groups* composed of *similar* tasks performed by two or more participants, then the projects could proceed. The intention was to ascertain a preliminary SI score (the product of all SI task parameter multipliers except duration per day) for a task group based on estimates conducted using archived video recordings for one, randomly selected individual task in the group. Later, the SI task parameter multiplier values for the representative individual task could be assigned to the other individual tasks in the task group.

B.2. Assignment of preliminary task groups

Prior to submitting the grant application for these studies, approximately 300 unique job tasks were identified based on the following minimum criteria:

- Other than inspection jobs, the tasks were located in the same *work area* of the plant. Examples of work areas:
    - Basepan
    - Crating
    - Shelving

    - microwave
- The tasks had the same unique purpose. Examples of unique purposes:
    - assembly basepan,
    - braze basepan,
    - secure lids onto the top of crates to prepare them for shipping,
    - install gaskets on doors,
    - program refrigerator water dispensers
- The force requirements of the task would be assigned the same SI intensity of exertion task parameter rating criterion category: Light, Somewhat Hard, Hard, Very Hard, or Near Maximal
- The same dominant hand was used

The following procedures were used to evaluate tasks in terms of the criteria listed above. First, basic descriptive task data (*e.g.* dominant hand, department, line number, shift, name of task) available from Iowa Study databases and records were reviewed and tasks were sorted. With the assistance of the Project Coordinator from the Iowa Study, all the tasks were sorted into two categories: 1) tasks with a unique function that were only performed by one participant (*unique, solitary tasks*) and 2) preliminary groups of two or more individual tasks with common *work elements* and similar force requirements (*task groups*). Based on the initial records review, a set of 122 unique, solitary tasks and 179 preliminary task groups were identified. Based on this preliminary assessment we decided that it was feasible to proceed.

B.3. Validating preliminary task group assignments

The next step was to validate the accuracy of preliminary task group assignments. To discriminate between tasks that met the criteria above for work area, useful purpose, and intensity of exertion rating criterion category, tasks were then evaluated based the degree of similarity for the following criteria:

- Similar frequency, duration, and type of power tools used
- The same or similar objects were handled
- The work elements in the task was the same or very similar. A *work element* is a functional part of a task that is associated with one or more *exertions*. For example:
    - remove the clear film protective coating from a stainless steel refrigerator door,
    - move a door from the conveyor and put it on a rack,
    - plug the holes in a refrigerator liner,
    - attach a skid to the basepan.

In a few instances, based on records for a task's work area, line number, shift, participant' recruitment date, and task description we were reasonably confident that the preliminary task group's assignments were accurate. In this case, we selected a few videos at random from the task group and watched the videos to confirm that the same task was being performed. For the majority of task groups a more thorough procedure was required to validate the accuracy of task group assignments. For this process, most of the videos for the tasks assigned to the group were viewed and detailed descriptions of the tasks were documented on paper or in a database. An example of the details recorded for a group of brazing tasks is presented in Table B1. At the end of the verification process, 162 unique, solitary tasks remained and 189 task groups were identified (Table 4.).

B.4. Discussion

Strain Index Studies I & II were both secondary analyses of previously collected data. With this type of study certain challenges are unavoidable because the field data was not collected to address the specific aims of the current study. Identifying and verifying homogenous exposure 'task groups' was one of the more challenging, and time consuming, aspects of the current study. Among the 351 tasks that were rated with the SI for this study, only 96 unique combinations of the five biomechanical SI task parameter multipliers were observed. In retrospect, perhaps a less detailed task classification procedure could have been developed.

Table B1. Example of video observation notes taken to verify accuracy of the preliminary task group several crating tasks.

preliminary task group code	Intensity of exertion	Taskcode	Work area	Video notes	Final task group code
o1_RH	light	020409	backside	bends tubes, braze dryers	h1_RH
o1_RH	light	220409	brazer	bends tubes, braze dryers	h1_RH
o1_RH	somewhat hard	930501	brazer	bend tubes, braze dryers, use screwgun 4 times at eye height	o1_RH
o1_RH	light	930501	backside	braze dryers, push tubes back inside	h1_RH

RH in task group code indicates participant was right-hand dominant; h1_RH was a previously existing code for a 'dryer brazing' task that was rated 'light'

APPENDIX C: CYCLE SELECTION RULES

Ideally, several cycles and several minutes of video should be viewed when using the SI, but this was not feasible for this dissertation. Instead, our goal was to use SI methods to rate at least one minute of video and at least one complete representative cycle. In the current study, SI raters were assigned specific segments of video to rate. Three representative work cycles (Cycle 1, Cycle 2, and Cycle 3) for each cyclic task had been previously identified for the Iowa Study. For cyclic tasks, the specific segments of video were selected based on the following rules:

- Among the three representative work cycles identified for the Iowa Study Cycle 2 was the default cycle assigned to SI raters as long as the following criteria were met:
  1. cycle duration for all representative work cycles was at least one minute,
  2. the difference in cycle duration (s) for Cycle 2 compared to Cycle 1 or Cycle 3 was not more than 25%, and
  3. A large proportion of the views of the hand/wrist in the video segment for Cycle 2 were poor or missing (> 30%) and views of the hand/wrist for Cycle 1 or Cycle 3 were substantially better.

When at least one of the three criteria listed above was not met, the following general rules were applied:

- **Rule 1:** Usually, when the difference in cycle duration (s) for Cycle 2 compared to Cycle 1 or Cycle 3 was more than 25% (criteria #2 above), then one cycle was much shorter or longer than the other two. In this case the ‘extreme’ cycle was selected in addition to one of the other representative cycles. When the three cycle durations were all somewhat different (> 25%), then the longest and shortest cycle durations were selected and rated. If the total duration of Cycle 1, 2, and 3 was less than one minute, the next rule was applied.

- **Rule 2:** If cycle duration was less than one minute for Cycle 1, 2, or 3 (criteria #1) then the objective was to select a combination of cycles with total duration of more than one minute. For tasks with very short cycle times (*e.g.* ten seconds), one consecutive minute of video was selected and the starting time for that segment was selected to maximize the inclusion of as many of the representative cycles as possible. To select a combination of cycles, the total duration was calculated for each of the following combinations, in order, until a combination of cycles with duration greater than one minute was identified:
    - Cycles 2 & 3,
    - Cycles 1 & 2,
    - Cycles 1 & 3,
    - Cycles 1, 2, & 3, or
    - one consecutive minute of video
- **Rule 3:** When a large proportion of the views of the hand/wrist in the video segment for Cycle 2 were poor (obstructed) or missing (> 30%) and views of the hand/wrist for Cycle 1 or Cycle 3 were substantially better, then Cycle 3 was selected by default.
- **Rule 4:** Lastly, if field notes from the Iowa Study indicated that an alternate strategy may be appropriate, then that information was incorporated into the decision process.

APPENDIX D: SI SCORE COMPUTATION METHOD

Notation

- Let SI be the SI score for a single-task calculated using the original formula SI = IE′ x HWP′ x SW′ x DE′ x EM′ x DD′, where IE′, HWP′, SW′, DE′, EM′, DD′ are multiplier values (Table 2.1.) for the six SI parameters: intensity of exertion (IE), hand/wrist posture (HWP), speed of work (SW), percent duration of exertion (DE), and efforts per minute (EM), and duration per day (DD)(Moore & Garg, 1995).
- Let CSI be the SI score for a multi-task job with *t* (*t* = 1, 2, . . . , *n*) tasks calculated using the CSI SI computation method.
- Let SI_t be the SI score for each task *t* ($SI_t = SI_t = IE'_t \times HWP'_t \times SW'_t \times DE'_t \times EM'_t \times DD'_t$) where IE'_t, HWP'_t, SW'_t, DE'_t, EM'_t, DD'_t, are multiplier values for the six SI parameters for task *t:* IE_t, HWP_t, SW_t, DE_t, EM_t, DD_t.

CSI Computation Method

Step 1

The first step for calculating the CSI for a for a multi-task job with *t* (*t* = 1, 2, . . . , *n*) tasks, is to calculate the SI_t for each task *t*: $SI_t = SI_t = IE'_t \times HWP'_t \times SW'_t \times DE'_t \times EM'_t$.

Step 2

The next step is to rank all SI_t in descending order *r* (*r* = 1, 2, . . . , *n*) by SI_t and DD_t.where $SI_{t_r} \geq SI_{t_{r+1}}$ and $DD_{t_r} \geq DD_{t_{r+1}}$. Therefore, SI_{t_1} is the highest SI_{t_r} value.

Step 3

For each task *t* with rank *r* calculate DD_r (cumulative hours worked through the current task (t_r)). For task *t* with rank $r \geq 2$ calculate DD_{r-1}(cumulative hours worked through the previous task (t_{r-1})):

$$\mathrm{DD}_r = \sum_{r=1}^{n} \mathrm{DD}_{t_\mathrm{r}}$$

$$\mathrm{DD}_{r-1} = \sum_{r=2}^{n} \mathrm{DD}_{t_{\mathrm{r}-1}}$$

Step 4

Calculate the incremental strain $\Delta\mathrm{SI}_{t_r}$ for task *t*, rank $r = 2$ through *n:* $\Delta\mathrm{SI}_{t_r} = \mathrm{SIprelim}_{t_r}(\mathrm{DD}'_r - \mathrm{DD}'_{r-1})$, where $\mathrm{SIprelim}_{t_r}$ is the SI score for task *t* and rank *r* independent of hours worked (assign the value of 1.0 to DD'_t): $\mathrm{SIprelim}_{t_r} = \mathrm{IE}'_{t_\mathrm{r}} \times \mathrm{HWP}'_{t_\mathrm{r}} \times \mathrm{SW}'_{t_\mathrm{r}} \times \mathrm{DE}'_{t_\mathrm{r}} \times \mathrm{EM}'_{t_\mathrm{r}}$.

Step 5

Finally, use SI_{t_1} and $\Delta\mathrm{SI}_{t_r}$ to calculate CSI for day *d* (d = 1, 2, . . . , 7, where 1 = Monday) as follows:

$$\mathrm{CSI}_d = \mathrm{SI}_{t_1} + \sum_{r=2}^{n} \Delta\mathrm{SI}_{t_r}$$

An sample calculation of CSI for a hypothetical job with four tasks of varying duration is presented in Table D1.

Software and Programming

SI scores for an entire shift were calculated in SAS® for all participants according formulas developed by Arun Garg, PhD, one of the investigators who published the original Strain Index article (Garg, 2006). Code used to calculate SI scores with the CSI method was adapted from Microsoft Excel macros developed at University of Wisconsin-Milwaukee by Kapellusch & Garg (personal communication, May 12, 2008). The SAS® CSI calculation program was tested for accuracy against CSI scores calculated both manually and with Microsoft Excel macros developed by Kapellusch & Garg. Additionally, the SAS® coding was reviewed by Jay Kapellusch, the programmer who developed the Microsoft Excel macro program used in Arun Garg's ergonomics laboratory.

Table D1. Sample Cumulative Strain Index multi-task SI score calculation for a job with four tasks (Tasks A, B, C, and D)

Task	rank (*r*)	SI score for task *t* in descending order *r* (SI_{t_r})	$\mathrm{SIprelim}_{t_r}$ for task *t*, rank *r*	Duration per day (DD) (h)	Cumulative Duration per day (h)	Multiplier value for cumulative duration per day (DD'_r)	Incremental SI score increase ($\Delta\mathrm{SI}_{t_r}$) ($\Delta\mathrm{SI}_{t_r} = \mathrm{SIprelim}_{t_r}(\mathrm{DD}'_r - \mathrm{DD}'_{r-1})$)
Task A	1	**6.5**	13	2.0	2.0	0.5	n/a
Task B	2	5.05	10.1	1.5	3.5	0.75	= 10.1 * (0.75 - 0.5) = **2.53**
Task C	3	3.0	3	4.0	7.5	1.0	= 3 * (1.0 - 0.75) = **0.75**
Task D	4	0.75	3	0.5	8.0	1.0	= 3 * (1.0 - 1.0) = **0**
						Multi-task SI Score (CSI) =	6.5 + 2.53 + 0.75 + 0 = **9.78**

$\mathrm{SIprelim}_{t_r}$ is the SI score for task *t* and rank *r* independent of hours worked (assign the value of 1.0 to DD'_t): $\mathrm{SIprelim}_{t_r} = \mathrm{IE}'_{t_r} \times \mathrm{HWP}'_{t_r} \times \mathrm{SW}'_{t_r} \times \mathrm{DE}'_{t_r} \times \mathrm{EM}'_{t_r}$.where IE'_{t_r}, HWP'_{t_r}, SW'_{t_r}, DE'_{t_r}, EM'_{t_r} are multiplier values (Table 2.1.) for task *t*, rank *r*, for the six SI parameters: intensity of exertion (IE), hand/wrist posture (HWP), speed of work (SW), percent duration of exertion (DE), and efforts per minute (EM), and duration per day (DD).

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