Quantifying the effects of experience on motor behaviors during simulated occupational tasks

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ABSTRACT

Work-related low back disorders (WRLBDs) are common and costly in the U.S. and numerous interventions aiming to reduce WRLBD risk have been developed. In one approach, training programs incorporating the work strategies (or work methods) of experienced workers have often been proposed as a training model or a behavior target of training. However, both the specific role of work experience in contributing to WRLBDs and the effectiveness of such an intervention approach are not well understood. In the current research, differential work strategies of experienced workers and associated WRLBD risk were identified, in the context of several common occupational activities. Three experiments were completed, in which both experienced workers and matched novices participated. These experiments involved relatively short duration repetitive lifts/lowers, more prolonged lifts/lowers that induced fatigue, and dynamic pushes/pulls. Diverse aspects of work strategies were quantified, emphasizing torso kinematics/kinetics, balance maintenance, and/or torso movement stability. During short-term repetitive lifts/lowers, experienced workers exhibited higher torso kinematics and kinetics, suggestive of a higher risk for WRLBDs, though better balance maintenance and torso stability were evident in this group. Thus, experienced workers may trade off an increased risk for WRLBDs to achieve better balance and torso stability. Fatigue modified work methods during repetitive lifts/lowers in both the novice and experienced groups, though the associated contribution to WRLBDs was unclear due to opposite changes in torso kinematics vs. kinetics. More consistently, fatigue decreased balance maintenance during lifts/lowers. Fatigue also modified work methods adopted by experienced workers, leading to higher torso kinetics, that were suggestive of a higher risk for WRLBDs during lifts/lowers. For dynamic pushes/pulls, experienced workers used lower torso kinematics and kinetics, suggestive of a lower risk for WRLBDs. As a whole, these results suggest that work methods are distinct between novices and experienced workers. Further, work experience may not consistently reduce WRLBD risk, and the influences of experience may be task specific. Such findings can help guide the development of future interventions, particularly training, targeting the control of WRLBDs.

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My family, I love you and see you soon in Korea.

Table of contents

List of Tables

List of Figures

Chapter 1. Introduction

1.1. Significance of work-related low back disorders

Low back disorders (LBDs) remain common and costly. Among the general population, roughly 60-80% of adults will experience a LBD at least once in their lifetime (Waddell and Burton 2001). More specifically, in 2010 work-related LBDs (WRLBDs) accounted for ~13% of all nonfatal workplace incidences involving work absenteeism in the U.S. (BLS 2011a). WRLBD costs are difficult to estimate accurately, since occupational injuries are likely underreported (Azaroff *et al.* 2002) and are often associated with indirect costs including personal loss of earnings and productivity loss (Lubeck 2003). Although estimated costs vary in the literature ($6-100 billion; Maetzel and Li 2002, Marras 2000), the economic impact is clear, since WRLBDs result in the highest portion (~20%) of all costs for all occupational injuries and illnesses (Leigh *et al.* 2006a). Apart from monetary losses, WRLBDs also reduce an individuals' quality of life due to disabilities, limited activities, and depression (Lubeck 2003). As documented by the National Institute for Occupational Safety and Health (NIOSH 1997), workers engaged in manual materials handling (MMH) are particularly at a high risk for WRLBDs. Kuiper et al. (1999) systemically evaluated more than two dozen publications, and concluded that MMH is a clear risk factor for WRLBDs, but also that additional studies were needed to assess more specifically the risks of such tasks, including lifting, lowering, pushing, and pulling.

1.2. Work experience and WRLBDs

WRLBDs can be caused or exacerbated by multiple factors including physical task demands, psychosocial factors, and individual differences (Burdorf and Sorock 1997, Manek and MacGregor 2005, Marras 2000). The latter is of particularly interest here, specifically individual differences in work methods related to work experience. Workplace interventions, in the context of MMH, have focused mainly on physical task demands. Such interventions typically involve some changes in the dimensions or configuration of a task, or changes in tools, equipment, etc. Interventions targeting psychosocial aspects have been used recently, but with mixed evidence as to effectiveness (Jellema *et al.* 2005, van der Molen 2005, van der Windt *et al.* 2008). Interventions addressing individual differences are usually achieved through some form of worker training. One intriguing approach to such training is the identification and incorporation of the work methods of experienced workers. Developing such training requires a sufficient understanding of the work methods used by experienced workers to enhance training efficacy. However, given mixed results regarding WRLBD risks, existing evidence has not fully confirmed whether the work methods associated with work experience are actually beneficial for worker training aiming at WRLBD prevention.

Some earlier studies have often concluded that experienced workers may use specific work methods that reduce WRLBD risk. In particular, several surveys indicate that novice workers are exposed to higher risks for WRLBDs, as evidenced by a higher initial WRLBD onset rate (van Nieuwenhuyse *et al.* 2004) and a larger number of claims due to WRLBDs (Bigos *et al.* 1986). Work methods adopted by experienced workers have been suggested to translate to lower stresses in the back during manual material handling (MMH) tasks (Chany *et al.* 2006, Lett and McGill 2006, Patterson *et al.* 1986), and to increase back muscle stiffness to maintain stable trunk postures as physical task demands increase during lifting (Granata *et al.* 1999, Marras *et al.* 2006). It has been also found that experienced workers exhibit lower levels of muscle activation (Keir and MacDonell 2004, Madeleine *et al.* 2003), avoid extreme postures and higher cumulative loads (Gregory *et al.* 2009a, Gregory *et al.* 2009b, Pal *et al.* 2010), and report higher maximum acceptable weights and lower perceived discomfort levels over 8-hour shifts (Mital 1987, Parakkat *et al.* 2007). In addition, novice workers have been successfully trained to mimic the specific work methods that have been reported to reduce WRLBD risks (Gagnon 1997, 2003, 2005).

In contrast, Plamondon et al. (2010) and Granata et al. (1999) found higher peak torso velocities and moments among experienced workers during lifting. These findings suggest that the work methods of experienced workers may not be consistently linked to lower risk for WRLBDs. A potential source of the discrepancy in these findings regarding the effects of experience on WRLBD risk is the lack of control of confounding effects such as age, anthropometry, or strength. Thus, additional studies that control these confounders are warranted, to help better understand specific roles of work experience in WRLBD occurrence. The current studies were designed to help understand the distinct work methods adopted by experienced workers, with an emphasis on the relationship of these methods to WRLBDs. Thus, several research gaps are reviewed in the following section.

1.3. Existing research gaps

Evidence indicates that there are skill-related differences between experts and novices. For example, kinematic and kinetic differences are well described in the context of sports (e.g., Blackwell and Cole 1994, Delay *et al.* 1997, Gatt *et al.* 1998, Okuda *et al.* 2010). While such evidence suggests that kinematics and kinetics can substantially change with experience and skill development, it is not directly relevant to the occupational domain and occupational injury prevention in particular, because, unlike athletes, workers are not typically trying to optimize an outcome (maximal forces, minimum time, etc.).

In the context of MMH, skill-related differences in kinematics and kinetics have also been reported, though these measures have only accounted for limited aspects of motor control. Developing effective work training programs, however, requires a sufficient understanding of "desirable" motor control strategies. As a working definition, motor control concerns the regulation of movements by central nervous system (CNS) activities. Although there are diverse ways to analyze motor control, an analysis at the behavioral level is of particular interest here to address gross motor control. Typical measures related to gross motor control involve movement, balance, and muscle activities. The former (movement and balance) are primary concerns in the current work because movement- or balance-related parameters (positions, velocities, force, etc.) are clearly results of motor commands and important sources of feedback information affecting CNS activity (Kakei *et al.* 1999, Prochazka *et al.* 1997, Schmidt and Lee 2005, Winter 2004a). This indicates that motor control strategies can be indirectly measured by observing worker's behaviors. Although recent studies have emphasized the importance of motor control and its influence on LBDs (McGill 2004, Preuss and Fung 2005), a relatively narrow set of measures (trunk kinematics and kinetics) have been investigated regarding the specific motor control strategies of experienced workers (e.g., Gagnon 1997, Granata *et al.* 1999, Marras *et al.* 2006, Patterson *et al.* 1986). These are considered inadequate to support development of comprehensive injury prevention programs. Further, these measures were obtained only during a few specific tasks such as lifting and static pushing/pulling.

In reviewing the literature with respect to motor control, three areas were identified as requiring further investigation: 1) additional aspects of motor control, such as balance and movement stability, 2) different physical conditions such as muscular fatigue, and 3) different task situations such as dynamic pushing and pulling. The following sections address the importance of each of these areas and discuss their relevance to WRLBDs.

1.3.1. Balance and movement stability

Balance is essential to motor control strategies. The primary purposes of human motor control are balance maintenance and movement execution (Massion *et al.* 2004), both of which are essential to whole body motions such as lifting, lowering, pushing, and pulling (Frank and Earl 1990). Postural instability, or a loss of balance, can impede movement and result in injuries such as WRLBDs. In particular, postural instability can result in higher levels of muscle activation and delayed muscle activation (Kollmitzer *et al.* 2002, Slijper and Latash 2000, Toussaint *et al.* 1997), both of which are associated with motor control errors that might cause WRLBDs. Despite the importance of balance in motor control, balance has been reported only rarely in the context of experienced workers' occupational tasks. In one study comparing the box-handling techniques of six novice and six experienced workers (Authier *et al.* 1996), better balance maintenance was observed for experienced workers. However, this study provided only anecdotal evidence in favor of the experienced workers, as opposed to quantifying or statistically evaluating balance differences between experienced and novice lifters.

Movement stability also provides important information, reflecting the stability of human motor control. Movement stability can be estimated from kinematic variance, and the latter is often considered as a motor control error that is possibly associated with WRLBDs. As supporting evidence, Granata et al. (1999) showed that WRLBD risks are related to kinematic or kinetic variance. In addition, movement stability can provide additional information unexplored by earlier studies. While earlier studies often treated kinematic variance as stochastic noise, emerging evidence suggests that such variance often serves as a functional component in movement (Oullier *et al.* 2006). In particular, investigating movement stability can provide additional information regarding experienced workers. Since evidence indicates that familiar movements exhibit stable patterns (Mégrot and Bardy 2006, Nourrit *et al.* 2003), experienced workers' behaviors might be better understood by measuring their relative movement stability in comparison to that of novices.

In conclusion, balance and movement stability reflect motor control strategies that are considered closely related to LBDs. It is anticipated, therefore, that quantitative studies would provide meaningful information about balance and movement stability of experienced workers.

1.3.2. Localized muscle fatigue

A number of studies have provided evidence that lifting-induced muscle fatigue can result in an increased risk of WRLBDs. For example, such fatigue increases the peak bending moment at the lumbar spine (Bonato *et al.* 2003, Dolan and Adams 1998), which appears to be related to decreased muscle performance and compromised motor control strategies. Such reduced performance and modified strategies have also been evidenced by reductions in back extensor strength and endurance time (Potvin and Norman 1993, Sparto *et al.* 1997) and changes in lifting techniques (Trafimow *et al.* 1993). In addition to increasing trunk loads, muscle fatigue deteriorates balance and postural stability, especially in terms of motor control systems including the CNS and relevant sensory feedback systems (Allen and Proske 2006, Björklund *et al.* 2000, Pline *et al.* 2005, Taimela *et al.* 1999). Nussbaum (2001) demonstrated that postural stability was altered by fatiguing the shoulder, a non-critical body part for balance maintenance during quiet stance; this finding also supports possible changes in motor control under localized muscle fatigue situations. In the context of lifting, Sparto et al. (1997) reported that postural stability decreased during lifting-induced fatigue tests. Although evidence is limited in the context of movements involving trunk flexion/extension without lifting a load, fatigue may also change dynamic torso stability (Granata and Gottipati 2008). Thus, muscle fatigue has the potential to contribute to WRLBDs due to its association with compromised motor control strategies.

Despite ongoing interest in muscle fatigue and its association with motor control, few studies have objectively measured the motor behaviors of experienced workers under controlled fatigue conditions. For example, earlier studies have examined psychophysical exertion levels or discomfort ratings of experienced workers during extended work periods (Mital 1987, Parakkat *et al.* 2007). Work by Marras et al. (2006) included objective measures such as back moments over eight hours, yet fatigue-related changes were not analyzed due to the lack of pre-fatigue measures. Although Mital et al. (1994) reported physiological changes of experienced workers during controlled fatigue trials, their measures, including heart rate and oxygen uptake, are highly related to individual training, such as personal fitness, and that are considered inappropriate for workplace training.

1.3.3. Dynamic pushing and pulling

While the literature associated with lifting tasks is fairly comprehensive, pushing and pulling tasks have been less well explored. As relevant studies, Lett & McGill (2006) reported that inexperience was associated with higher lumbar moments during static pulling tasks, while Chang et al. (2000) demonstrated that individuals who practiced a pulling task were able to reduce lumbar torques. These studies, however, only investigated static pushing/pulling tasks, whereas dynamic efforts represent over 90% of the pushing and pulling tasks in industry (Ciriello *et al.* 1999).

Workers' motor control strategies may differ during static and dynamic pushing/pulling tasks, since the mechanical environments are different. For a task to involve dynamic pushing and pulling, initial static friction must be overcome to initiate movement. Thereafter, static friction is reduced to dynamic friction that should be overcome to maintain movement. A common example of a dynamic pushing and pulling task in industry would be a worker who uses a hand-cart to move a large or heavy load. Due to reduced dynamic friction, the motor control strategies during a static condition followed by movement are clearly different from the strategies during only a static condition. Moreover, any sudden changes in friction forces may generate perturbations to movement or balance during the dynamic pushing and pulling tasks, thereby impacting low back moments (Chow *et al.* 2002). Thus, it is considered that investigating dynamic pushing/pulling has particular applied value in efforts to prevent WRLBDs (as well as fall risks).

1.4. Summary

As discussed, existing evidence demonstrates that trunk kinematics and kinetics differ between experienced and inexperienced workers during lifting and static pushing/pulling. However, evidence of an effect of work experience on balance and motion stability remains relatively sparse, as are studies assessing work experience effects in the context of lifting-induced fatigue and dynamic pushing/pulling conditions. The present work addresses these gaps by quantifying experience-related differences in motor behaviors. This work identified work methods adopted by experienced workers that are distinct from those of novices; in future efforts, these findings may guide developing training programs to reduce WRLBD risk. This dissertation is organized with one chapter for each study. Chapter 2 addresses work method differences between novice and experienced workers during short-term repetitive lifts/lowers focusing on torso kinematics and kinetics. Chapter 3 addresses differences in balance and torso movement stability between novices and experienced workers during the tasks employed in Chapter 2. Chapter 4 addresses differences in fatigue-induced changes between novice and experienced workers during relatively longer-term repetitive lifts/lowers. Chapter 5 addresses work method differences between novice and experienced workers during pushes/pulls. Finally, Chapter 6 provides a summary of the major findings, practical implications, and suggestions for future studies.

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Chapter 2: Experienced workers exhibit distinct torso kinematics/kinetics and patterns of task dependency during repetitive lifts and lowers

Jungyong Lee and Maury A. Nussbaum

Abstract

Individual differences in work methods may be related to the risk of injury during manual material handling tasks, yet existing evidence comparing experienced workers and novices is mixed. This study assessed torso kinematics and kinetics among six experienced workers and six novices during repetitive lifts/lowers under different task configurations (symmetric vs. asymmetric and lift vs. lower). Several important potential confounding effects were controlled. Peak kinematic and kinetic measures were typically higher among experienced workers and suggestive of exposure to higher levels of low-back injury risk, though overall exposure levels were moderate. Work methods used by experienced workers were modified between task conditions, whereas novice behaviors were more consistent. Control of torso kinematics/kinetics may thus not be a primary factor in determining experienced worker's work methods, and future investigation is needed to establish if, or under what conditions, these methods are protective and/or should be the basis for interventions including training.

Keywords: experience; low back; asymmetry; lifting; lowering; biomechanics

2.1. Introduction

Low back disorders (LBDs) remain common and costly. Among the general population, 60-80% of adults will experience a LBD at least once in their lifetime (Deyo *et al.* 1991, Waddell and Burton 2001). More specifically, work-related LBDs (WRLBDs) accounted for nearly a half of all musculoskeletal disorder cases involving work absenteeism in the U.S. in 2010 (BLS 2011b). Costs associated with these are substantial (Dagenais *et al.* 2008, Maetzel and Li 2002, Marras 2000), with WRLBDs resulting in the highest portion (~20%) of all costs for all occupational injuries and illnesses (Leigh *et al.* 2006b). Workers engaged in manual materials handling (MMH) are particularly at high risk for WRLBDs (Hoozemans *et al.* 1998, Kuiper *et al.* 1999, NIOSH 1997) and lifting or lowering tasks are considered an important risk factor (da Costa and Vieira 2010), especially under asymmetric conditions (Cole and Grimshaw 2003, Hoogendoorn *et al.* 2000, Marras *et al.* 1995).

WRLBDs can be caused or exacerbated by multiple factors including physical task demands, psychosocial factors, and individual differences (Burdorf and Sorock 1997, Manek and MacGregor 2005, Marras 2000). The latter is of particular interest in the present study, specifically individual differences in work methods related to work experience. In the context of MMH, workplace interventions have focused mainly on physical task demands, typically by changing the dimensions or configuration of a task, or changing tools, equipment, etc. (van der Molen *et al.* 2005). Interventions targeting psychosocial factors have been used recently, but with mixed evidence as to effectiveness (Jellema *et al.* 2005, van der Windt *et al.* 2008). Interventions addressing individual differences are usually achieved through some form of worker training, with a major goal of influencing (improving) work methods. One intriguing approach to such training is the identification and incorporation of the work methods adopted by experienced workers. In addition, it is possible that novice workers can be trained to mimic the methods of experienced workers in beneficial ways (Gagnon 2003, 2005), and training has been widely advocated in industry (Lahiri *et al.* 2005), especially where engineering controls are not feasible or possible.

Developing such training requires a sufficient understanding of desired work methods. In existing literature, experienced workers are generally considered to have distinct lifting strategies, and to adopt methods associated with a lower risk of WRLBDs. Novice workers are likely exposed to higher risks for WRLBDs, as evidenced by a higher initial WRLBD onset rate (van Nieuwenhuyse *et al.* 2004) and a larger number of claims due to WRLBDs (Bigos *et al.* 1986). While these results, based on surveys, may be limited in supporting causality, other evidence also indicated that healthy experienced workers may have developed beneficial work methods for preventing WRLBDs (Authier *et al.* 1996, Gagnon 1997). Specifically, such work methods have been suggested to translate to lower stresses in the back (Marras *et al.* 2006, Patterson *et al.* 1986) and to increase back muscle stiffness to maintain a stable torso posture (Granata *et al.* 1999) during lifting. Experienced workers also appear to avoid extreme postural deviations (Pal *et al.* 2010) and exhibit lower muscle activation levels (Keir and MacDonell 2004) that may reduce low back loads during lifting. Similar findings have been reported for tasks other than lifting (Gregory *et al.* 2006, Madeleine *et al.* 2003). In addition, inexperienced workers have tended to underestimated maximum acceptable weights (Mital 1987) and reported higher discomfort levels (Parakkat *et al.* 2007) over an eight-hour shift.

In contrast to such evidence, however, Granata *et al.* (1999) found higher lumbar moments among experienced workers, though other studies reported comparable or lower lumbar moments (Marras *et al.* 2006, Plamondon *et al.* 2010, Plamondon *et al.* 2012). Conflicting results have also been found for torso velocities; Plamondon *et al.* (2010) observed higher torso flexion/extension velocities among experienced workers, whereas Granata *et al.* (1999) reported the opposite. Such discrepancies may stem from different task configurations and/or different variables controlled in the respective experiments. In any case, further investigation seems warranted regarding the work methods of experienced vs. novice workers in the context of lifting, with a long-term goal of guiding training methods. Generally, training can be effective if the training model (in this case, the work methods of experienced worker) and training methods are well developed. In this study, we focused on the model. Since existing evidence is conflicting, as described above, it is unclear whether the experienced workers' work methods are an appropriate model for training intended to reduce WRLBDs. Thus, the effects of work experience should be better understood if training is to be based on experienced workers' behaviors. In particular, to build on prior work, this study sought to control for more potential influences (or confounding variables) including age, gender, strength, and anthropometry that were not fully addressed in earlier studies. Two specific hypotheses were thus addressed in the current study. First, that lifting methods adopted by experienced workers are not consistently associated with a lower risk of WRLBDs, as indicated by a range of biomechanical measures. Second, that differences in lifting methods between experienced and novice workers are task-dependent. In the present study, the focus is on lumbar kinematics and kinematics, as these are common biomechanical measures associated with WRLBD risk.

2.2. Methods

2.2.1. Participants

Twelve individuals completed the study, with equal numbers in two groups (experienced and novice workers), and with five males and one female in each group (Table 2.1). *A priori* power analysis confirmed that this sample size provided adequate statistical power (≥ 0.8) to detect effect sizes found in an earlier, related study (Granata *et al.* 1999). Although expertise can be associated with or assessed by multiple factors, including the duration of experience, peer evaluations, occupational ranks, etc. (Hoffman *et al.* 1995), the duration of experience is a common criterion since expertise generally develops over time with practice (Farrington-Darby and Wilson 2006).

Table 2. 1. Participant information (means (SD)) and results of *t*-tests comparing the Experienced and Novice groups.

	Age (yrs)	Experience (yrs)	Stature (m)	Body Mass (kg)	Lumbar Extensor Strength (Nm)	
					Concentric	Eccentric
Experienced	25.9 (5.9)	7.5 (4.3)	1.75 (0.09)	72.68 (10.24)	314.7 (68.5)	359.8 (76.7)
Novice	26.0 (5.3)	0.0 (0.0)	1.73 (0.06)	70.80 (9.69)	301.7 (52.6)	374.3 (45.2)
Test result	$t = 0.003$ $p = 0.96$	- -	$t = 0.46$ $p = 0.51$	$t = 0.11$ $p = 0.75$	$t = 0.14$ $p = 0.72$	$t = 0.16$ $p = 0.70$

Here we emphasized the duration of experience, and experienced workers were defined as healthy workers with substantial work experience. Experienced workers were recruited from among those working at local warehouses, construction sites, and farms. All reported a minimum of three years of recent experience in "frequent lifting tasks", which were operationally defined as lifting/lowering tasks conducted for at least 10 hours per week on average, similar to the criterion used by Patterson *et al.* (1986). Novices were recruited from among a pool of local students who responded to an advertisement. Participation was limited to those who had no experience in "frequent lifting tasks", and specific participants were selected so that the two groups were age-matched (± one year) at the individual level. All participants reported no current or prior musculoskeletal disorders and completed informed consent procedures approved by the Virginia Tech Institutional Review Board (Appendices A and B).

2.2.2. Experimental protocols

Since strength differences between the groups could serve as a confounding effect, isokinetic lumbar extensor strength (a key capacity related to the lifting tasks investigated here) was measured initially for each participant. Maximum voluntary isokinetic concentric/eccentric contractions were performed with a commercial dynamometer (Biodex System 3 pro, Biodex Medical Systems Inc., NY, USA). After initial warm-up and a rest period (~five min), a minimum of five trials, interspersed with two-min rest breaks, were completed at 120°/s with a range of motion of 0° - 80° of torso flexion. These specific testing conditions were selected to achieve high reliability (Keller *et al.* 2001).

Figure 2.1. Task configurations using during symmetric (left) and asymmetric lifts/lowers (right).

Each participant completed two sets of lifting tasks, involving repetitive lifting and lowering, in two asymmetry conditions (0° = sagittally symmetric vs. 60° asymmetric). Exposure order was counterbalanced and sufficient rest (~10 min) was provided between the two sets. Each set of lifting tasks was preceded by practice (10 lifts and lowers) and rest periods (~10 min) were provided between sets to minimize fatigue. In each set, participants repetitively (20 times) lifted and lowered a box ($33 \times 59 \times 24$ cm^3, with cut-out handles 21 cm from the bottom) with a mass set to 10% of individual body mass.

Participants continuously held the box throughout each set. Lifting frequency was set to 10/min and controlled using an electronic metronome. These specific conditions were selected based on pilot work, to assure that the task demands were moderate and that there was minimal development of whole-body or localized muscle fatigue.

During symmetric lifting, both the origin and destination were anterior to the participant in the mid-sagittal plane; for asymmetric lifting, the destination was rotated 60° to the right (it was assumed that any effects of asymmetry direction, left vs. right, are minimal). Participants self-selected the horizontal distance from the midpoint of their ankles to the lifting origin/destination during initial practice, and this distance was kept constant across all conditions. Using adjustable platforms, the vertical location of the box at the origin/destination was set so that the top of the box was at the participant's knee/elbow joints (Figure 2.1). These specific conditions were intended as representative of task configurations present in industrial lifting tasks (Ciriello *et al.* 1999, Dempsey 2003). The mean (SD) box mass and height of the top of box at the origin/destination were, for the experienced vs. novice workers respectively, 7.3kg (1.0kg) vs. 7.1kg (1.0kg), 52.3cm (2.2cm) vs. 53.3cm (1.9cm), and 125.2cm (5.0cm) vs. 122.1cm (4.2cm). A freestyle method was adopted for lifting/lowering, with no other specific instructions regarding work methods provided, as in earlier related studies (Marras *et al.* 2006, Plamondon *et al.* 2010).

2.2.3. Data collection and processing

Postures were monitored using reflective markers, which were tracked at 100 Hz with a 7-camera system (Vicon Motion System Inc., CA, USA). Markers were attached over anatomical landmarks as described by Dumas *et al.* (2007). To improve accuracy, additional markers were attached over relatively immobile body parts: vertebral process of T10 (torso), mid-way between bilateral posterior superior iliac spines (pelvis), and the anterior borders of the tibias (shank). Ground reaction forces and moments were measured using two force platforms (OR6-7-1000, AMTI, MA, USA), and sampled at 1000Hz. Motion and force data were low-pass-filtered (zero-lag, 2nd-order Butterworth) in software with respective cut-off frequencies of 5 and 10 Hz, and force data were down-sampled to 100Hz to be consistent with the motion data. From each set of 20 lifts and 20 lowers, the first five lifts and lowers were excluded to minimize start-up effects, and thus 15 lifts and lowers were used for subsequent data processing. Initiation and termination times for both lifting and lowering were identified using the vertical velocity of the box.

2.2.4. Dependent measures

Multiple measures were obtained to describe work methods, specifically addressing initial foot distance and torso kinematics / kinetics. A 3D linked-segment model with 15 body segments (and a box) was developed, with segmental masses, inertial tensors, and center-of-mass (COM) locations based on scaling methods in Dumas *et al.* (2007). The initial foot distance (D) was calculated as the horizontal distance from the mid-point of the two ankles to the box COM at initial lifting and lowering instants. Torso kinematics were derived (as in Winter, 2004a), specifically peak triaxial torso angles, angular velocities, and angular accelerations. For angular velocities and accelerations, five-point derivatives were employed, as in Kingma *et al*. (1998). This was done using Euler angles about the X (flexion/extension = FE), Y (lateral bending = LB), and Z (twisting = TW) axes, and with an XYZ rotation sequence. Torso kinetics included peak and cumulative triaxial L5S1 moments using a “bottom-up” approach as described by Kingma *et al*. (1998). Cumulative moments were determined as the sum of absolute values of instantaneous moments per hour duration during each lift or lower. Moments were normalized to minimize any influence of anthropometric differences (Hof 1996), and converted to the original units by multiplying mean stature and body mass across participants (to facilitate comparisons with published values). Calculation of scaled moment (M_s) was done using:

$$M_s = (\mu_m \times \mu_h)\,\frac{M}{m \times h} \tag{1}$$

where *m* and *h* are the body mass and the stature of a participant, respectively; μ_m is the mean participant body mass (71.7 kg); and μ_h is the mean participant stature (1.74 m). All measures of kinematics and kinetics were calculated with respect to segmental coordinate systems, and all peak measures were determined from absolute values. Two additional sets of measures were obtained. First, the timing at which peak kinematic/kinetic values occurred were identified, and represented as percentages of the duration of a given lift or lower. Second, and as described below, the variability of kinematic/kinetic measures within and between participants was determined using variance components (VC; s^2).

2.2.5. Statistical analysis

Three-way, full factorial, mixed-factor analyses of kinematic and kinetic measures were performed with experience (E), asymmetry (A), and lift/lower (L) as independent variables. Initial MANOVA and subsequent repeated measures ANOVA tests (for each kinematic/kinetic measure) were used, with post-hoc pairwise comparisons done using Tukey's Honestly Significant Difference (HSD). Within- and between-participant variances were calculated using Restricted Maximum Likelihood (REML) methods, similar to recent work by Fethke *et al.* (2012). Specifically, a nested model was developed including participant and repetition as random effects. Statistical analyses were done using JMP™ (v9, SAS Institute Inc., NC, USA), with significance concluded when $p < 0.05$, and summary results are presented as means. The presentation of results focuses only on main and interactive effects related to experience (effects related solely to asymmetry and lift vs. lower were consistent with expectations and extensive existing evidence).

2.3. Results

No significant or substantial differences were evident between the experienced and novice groups, in terms of age, anthropometry, or lumbar extensor strength (Table 2.1). MANOVA indicated that the main effect of experience and all interactive effects with experience were significant ($p < 0.001$). For univariate responses, there were several significant differences between experienced and novice workers in initial foot distance, torso kinematics, and torso kinetics (summarized in Table 2.2), and some significant differences between experienced and novice workers on selected measures during the same task configuration (summarized in Table 2.3). The results are described in more detail below, separately for each set of dependent measures since each dependent measure addresses different dynamic characteristics (and correlations among these were generally low-moderate).

Table 2.2. ANOVA results for main and interactive effects of experience (E), asymmetry (A), and lift vs. lower (L). Values shown in bold are significant ($p < 0.05$), while those in italics approached significance ($0.05 \leq p \leq 0.06$).

		Statistics*	E	E×A	E×L	E×A×L
Initial foot distance	D	*F*	**9.65**	2.68	**14.23**	*3.69*
		p	**0.011**	0.10	**<0.001**	*0.055*
Peak lumbar angle	FE	*F*	1.04	*3.66*	0.42	0.004
		p	0.33	*0.056*	0.51	0.95
	LB	*F*	1.17	**23.45**	**4.22**	**9.32**
		p	0.30	**<0.001**	**0.04**	**0.002**
	TW	*F*	4.41	**151.60**	2.95	**4.98**
		p	0.062	**<0.001**	0.086	**0.026**
Peak lumbar angular vel.	FE	*F*	*4.84*	0.41	**38.57**	**6.21**
		p	*0.052*	0.52	**<0.001**	**0.013**
	LB	*F*	3.88	3.50	0.43	**5.30**
		p	0.077	0.062	0.51	**0.022**
	TW	*F*	3.30	**28.20**	**10.66**	**3.97**
		p	0.10	**<0.001**	**0.001**	**0.047**
Peak lumbar angular acc.	FE	*F*	**5.80**	1.13	**51.61**	**8.54**
		p	**0.037**	0.29	**<0.001**	**0.004**
	LB	*F*	**6.75**	**37.72**	0.75	*3.65*
		p	**0.027**	**<0.001**	0.39	*0.056*
	TW	*F*	*4.82*	**4.93**	**11.15**	1.39
		p	*0.053*	**0.027**	**0.001**	0.24
Peak lumbar moment	FE	*F*	**14.27**	2.18	**94.19**	1.76
		p	**0.004**	0.14	**<0.001**	0.18
	LB	*F*	0.19	1.40	0.28	1.71
		p	0.67	0.24	0.60	0.19
	TW	*F*	1.70	**13.87**	**45.48**	**13.49**
		p	0.22	**<0.001**	**<0.001**	**<0.001**
Cum. lumbar moment	FE	*F*	1.08	**22.30**	2.87	**5.04**
		p	0.32	**<0.001**	0.091	**0.025**
	LB	*F*	0.70	**31.37**	1.81	0.02
		p	0.42	**<0.001**	0.18	0.89
	TW	*F*	0.22	**16.58**	**27.11**	1.61
		p	0.65	**<0.001**	**<0.001**	0.21

FE = flexion/extension, LB = lateral bending, TW = twisting

* Degrees of freedom (num, den) for each F statistic are: E (1,10), E×A (1,702), E×L (1,702), and E×A×L (1,702)

Table 2.3. Effects of experience in different task configurations. Mean (SD) values shown in bold are significantly ($p < 0.05$) different between groups.

		Group	Task Type 0°↑	0°↓	60°↑	60°↓
Initial foot distance (m)	D	Exp	0.40 (0.04)	0.78 (0.03)	0.40 (0.04)	**0.85 (0.03)**
		Nov	0.37 (0.02)	0.73 (0.02)	0.37 (0.07)	**0.78 (0.10)**
Peak lumbar angle (deg)	FE	Exp	38.6 (11.2)	40.5 (10.6)	38.5 (13.3)	40.6 (13.1)
		Nov	31.3 (10.6)	32.9 (10.1)	32.3 (11.1)	34.0 (10.0)
	LB	Exp	2.2 (1.1)	2.1 (0.8)	5.0 (3.2)	5.4 (2.7)
		Nov	1.4 (1.1)	1.8 (1.3)	4.4 (2.0)	4.7 (2.1)
	TW	Exp	**4.8 (2.7)**	4.1 (2.0)	21.2 (8.6)	20.5 (6.2)
		Nov	**2.2 (1.2)**	2.3 (1.3)	19.8 (2.5)	19.4 (2.5)
Peak lumbar angular vel. (deg/s)	FE	Exp	45.3 (12.5)	42.6 (13.9)	53.1 (17.8)	45.1 (17.1)
		Nov	36.7 (12.0)	26.5 (7.5)	38.8 (8.3)	29.3 (5.9)
	LB	Exp	5.3 (3.9)	4.8 (3.5)	11.6 (4.1)	12.0 (4.1)
		Nov	3.4 (2.0)	3.6 (2.1)	8.0 (2.6)	7.6 (2.6)
	TW	Exp	8.6 (5.5)	7.5 (5.3)	42.0 (13.1)	39.2 (9.1)
		Nov	4.9 (1.7)	5.1 (1.8)	34.2 (6.8)	33.8 (5.5)
Peak lumbar angular acc. (deg/s^2)	FE	Exp	168.1 (69.6)	149.2 (92.7)	198.8 (79.5)	155.4 (76.4)
		Nov	125.6 (45.0)	75.1 (25.8)	125.4 (34.7)	81.5 (16.3)
	LB	Exp	28.1 (26.1)	26.0 (20.9)	57.2 (26.8)	**71.6 (26.0)**
		Nov	17.0 (8.4)	18.0 (10.6)	32.5 (13.9)	**34.0 (8.2)**
	TW	Exp	47.0 (31.6)	40.6 (29.2)	148.1 (50.4)	134.8 (43.6)
		Nov	25.2 (9.0)	27.0 (12.9)	100.5 (26.2)	100.5 (24.9)
Peak lumbar moment (Nm)	FE	Exp	**166.6 (36.2)**	141.3 (21.6)	**151.4 (43.0)**	140.4 (24.4)
		Nov	**101.6 (29.5)**	102.2 (18.6)	**86.0 (21.9)**	94.7 (11.8)
	LB	Exp	34.4 (23.9)	31.3 (21.4)	104.7 (69.3)	103.8 (64.7)
		Nov	34.9 (15.8)	33.7 (16.3)	99.8 (33.6)	89.6 (28.3)
	TW	Exp	20.7 (15.1)	20.2 (13.6)	28.0 (18.1)	30.8 (14.8)
		Nov	11.4 (5.6)	10.2 (4.6)	22.6 (11.3)	17.4 (9.0)
Cumulative lumbar moment (kNm/hr)	FE	Exp	347.4 (116.2)	391.3 (115.3)	377.3 (163.1)	421.0 (203.9)
		Nov	321.8 (144.1)	336.2 (108.3)	258.7 (103.2)	305.9 (79.1)
	LB	Exp	114.1 (90.1)	111.6 (89.2)	270.2 (207.0)	257.6 (193.9)
		Nov	113.7 (66.8)	117.6 (68.3)	341.9 (140.0)	338.8 (120.1)
	TW	Exp	45.3 (33.6)	53.4 (35.7)	64.4 (39.9)	77.8 (45.4)
		Nov	32.4 (19.0)	32.8 (20.5)	62.1 (29.8)	58.2 (35.3)

Exp = experienced group, Nov = novice group

0° = symmetric lift/lower, 60° = asymmetric lift/lower

↑ = lift, ↓ = lower

2.3.1. Initial foot distance

Initial foot distances (D) were significantly influenced by experience. Experienced workers overall placed their feet ~5cm (~9%) further from the box than novices, and this difference was greatest during asymmetric lowers. Although significant or marginal interactive effects were found, these effects were rather small and experienced workers consistently adopted larger initial foot distances in all task configurations.

2.3.2. Kinematics

2.3.2.1. Peak lumbar angle

While there were no significant main effects of experience, peak lumbar angles were consistently higher among experienced workers than novices. The magnitude of this difference was most pronounced in the FE direction; experienced workers overall used ~7° (~21%) more torso flexion. Peak FE and LB lumbar angles were not significantly different between the two groups in any of the task configurations. TW angles, however, were significantly larger among experienced workers during symmetric conditions, especially lifts. Although some significant interactive effects with experience were found (i.e., on peak LB and TW angles), the magnitudes of these effects were small with no substantial differences in the pattern of responses (Table 2.3).

2.3.2.2. Peak lumbar angular velocity

Similar to peak angles, there were no significant main effects of experience, though with consistently higher values among experienced workers. Main effects on the triaxial velocities all approached significance, with experienced workers overall adopting ~14°/s

(~42%) higher FE velocities, ~3°/s (~49%) larger LB velocities, and ~5°/s (~25%) higher FW velocities. Several significant interactive effects were found, the more substantial of which were related to FE and TW velocities (Figure 2.2). Experienced workers used slightly (~12%) higher FE velocities during lifts vs. lower, while novices exhibited much a larger (~35%) difference in FE velocities between lifting and lowering. This pattern was especially apparent in the symmetric condition. Further, especially in the asymmetric condition, experienced workers used higher TW velocities during lifts vs. lower, whereas novices had similar TW velocities for lifts and lowers.

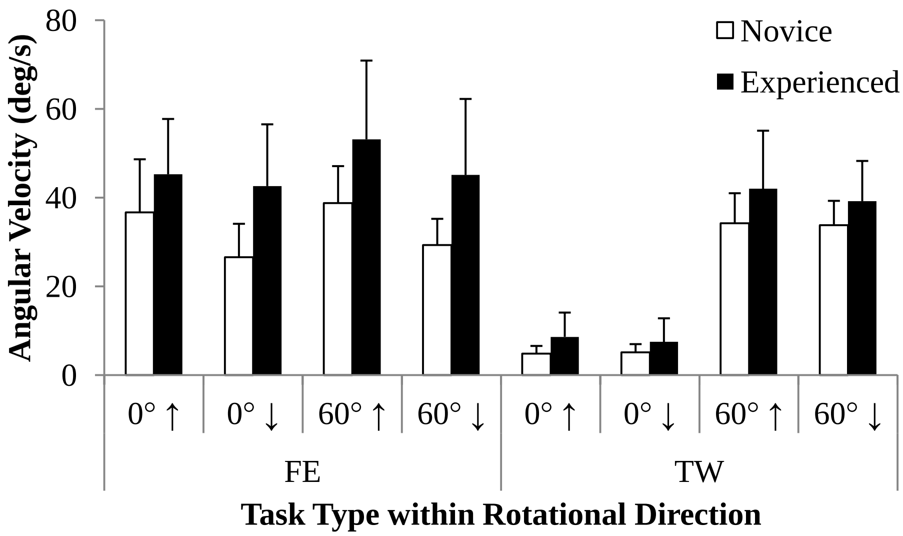

Figure 2.2. Mean values of peak lumbar angular velocities (FE = flexion/extension; TW = twisting) in different task conditions (0°↑ = symmetric lift; 0°↓ = symmetric lower; 60°↑ = asymmetric lift; 60°↓ = asymmetric lower). Errors bars indicate SDs.

2.3.2.3. Peak lumbar angular acceleration

All peak lumbar accelerations were significantly or marginally affected by experience, with respective ~66°/s^2 (~65%), ~20°/s^2 (~80%), and ~29°/s^2 (~46%) higher values among experienced workers in the FE, LB, and TW directions. In particular, experienced workers used ~31°/s^2 (~93%) higher LB accelerations during asymmetric tasks, and had ~38°/s^2 (~111%) higher values during asymmetric lowers. Several significant interactive effects were found; of these, the most interesting effects occurred on FE and LB accelerations. FE interactive patterns were similar to those for FE velocities as described above. For LB accelerations, novices exhibited similar peak values for both lifts and lowers in both asymmetry conditions (Figure 2.3). In contrast, experienced workers had slightly higher peak LB accelerations during lifts vs. lowers in the symmetric condition, but lower peak LB accelerations during lifts vs. lowers in the asymmetric condition.

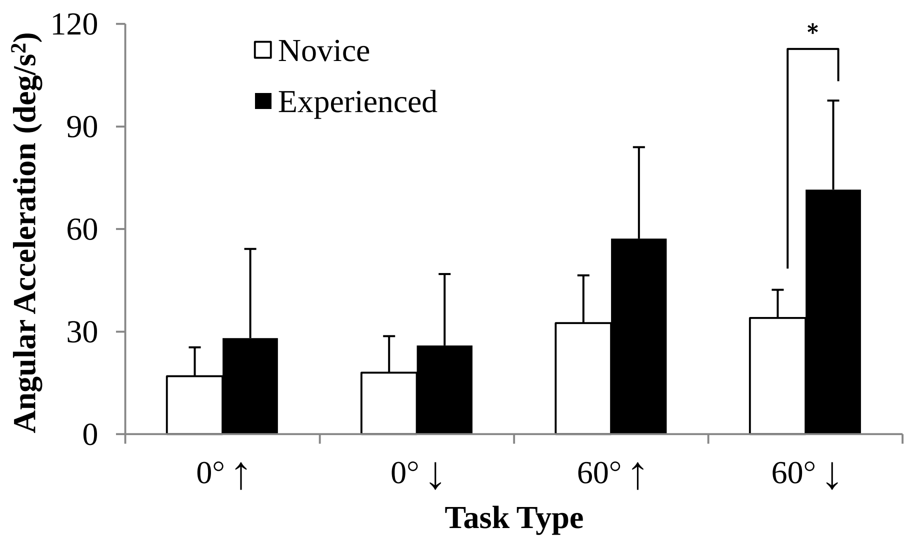

Figure 2.3. Mean values of peak lumbar lateral bending accelerations in different task conditions (0°↑ = symmetric lift; 0°↓ = symmetric lower; 60°↑ = asymmetric lift; 60°↓ = asymmetric lower). The symbol * indicates a significant difference between novice and experienced workers, and errors bars indicate SDs.

2.3.3. Kinetics

2.3.3.1. Peak lumbar moment

Peak lumbar FE moments were significantly influenced by experience, being overall ~54Nm (~56%) higher among experienced workers. There were also several significant interactive effects with experience on peak FE and TW moments, with those involving the E×L interaction being qualitatively important (Figure 2.4). Experienced workers had higher peak FE moments during lifts vs. lowers, whereas novices had lower FE moments during lifts vs. lowers. In the TW direction, the exact opposite relationship was evident. In both directions, differences between experienced and novice workers were more apparent in asymmetric conditions.

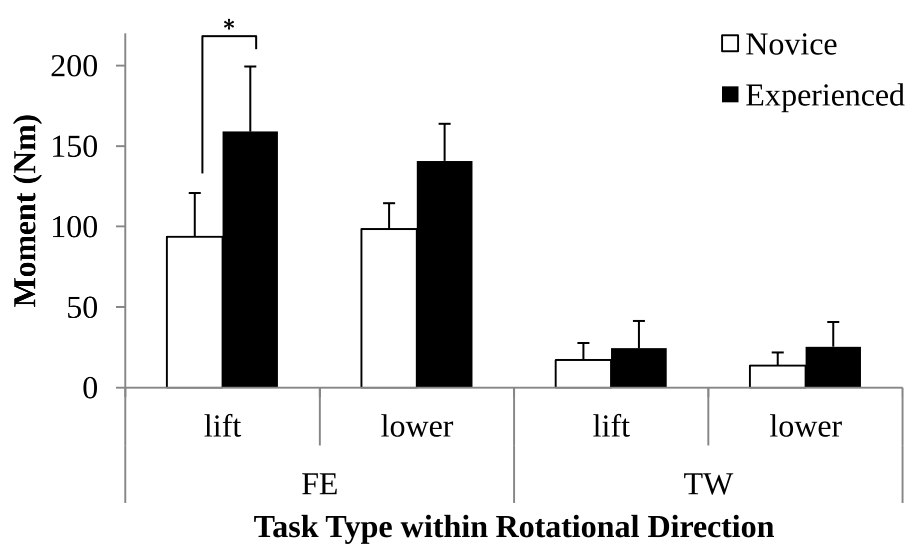

Figure 2.4. Mean values of peak lumbar moments (FE = flexion/extension; TW = twisting) in different task during lift and lower tasks. The symbol * indicates a significant differences between novice and experienced workers, and errors bars indicate SDs.

The largest differences (~65.3 Nm) in peak FE moment between experienced and novice workers were found during lifts. At the times these peaks occurred, moment components were decomposed to the moment due to posture (torso statics), linear and angular accelerations of the torso, box location (box statics), and linear and angular accelerations of the box (Table 2.4). For the former two, torso masses were estimated using existing scaling methods (Dumas *et al.* 2007). From this analysis, the majority of the difference in peak moments was due to differences in torso posture and accelerations.

Table 2.4. Torso and box parameters at the time of peak flexion/extension moments, and moment decomposition of the largest peak FE moment differences during lifts. Mean values are presented separately for the Experienced and Novice groups, "diff" = Experienced – Novice means, and "% of total" indicates the contribution of differences in each component to the overall difference of 65.3 Nm. Note, only contributions of the torso and box were considered here (upper extremities and head made minor contributions).

	Torso parameters at peak moment						
	$D_{T(V)}$	$D_{T(H)}$	α_T	$a_{T(V)}$	$a_{T(H)}$	m_T	I_T
Experienced	0.054m	0.275m	185deg/s^2	0.86m/s^2	-0.32m/s^2	24.2kg	0.46kgm^2
Novice	0.211m	0.206m	60deg/s^2	0.21m/s^2	-0.21m/s^2	23.6kg	0.45kgm^2

	Box parameters at peak moment					
	$D_{B(V)}$	$D_{B(H)}$	α_B	$a_{B(V)}$	$a_{B(H)}$	m_B
Experienced	-0.567m	0.527m	122deg/s^2	3.28m/s^2	-1.23m/s^2	7.3kg
Novice	-0.046m	0.495m	192deg/s^2	1.58m/s^2	-0.72m/s^2	7.1kg

	Moment components						
	Torso				Box		
	Posture	Lin. acc$_{(V)}$	Lin. acc$_{(H)}$	Ang. acc	Position	Lin. acc$_{(V)}$	Lin. acc$_{(H)}$
Experienced	66.6Nm	20.9Nm	7.6Nm	1.5Nm	37.4Nm	23.3Nm	-8.8Nm
Novice	48.5Nm	5.1Nm	4.8Nm	0.5Nm	35.2Nm	11.2Nm	-5.1Nm
diff	18.1Nm	15.8Nm	2.8Nm	1.0Nm	2.2Nm	12.1Nm	-3.7Nm
% of total	27.7%	24.2%	4.3%	1.5%	3.4%	18.5%	-5.7%

D: distance from the lumbar joint center (LJC) to center of mass (anterior/superior = +), α: angular acceleration (extension = +), a: linear acceleration (anterior/superior = +), m: mass, I: moment of inertia (about COM), subscripts (T: torso; B: box; V: vertical; H: horizontal)

2.3.3.2. Cumulative lumbar moment

There were no significant main effects of experience, though overall experienced workers were exposed to ~79 kNm/hr (~26% = ~66Nm/lift) higher FE moments, ~40 kNm/hr (~17% = ~33Nm/lift) lower LB moments, and ~14 kNm/hr (~30% = ~12Nm/lift) higher TW moments. Among several significant interactive effects, the E×A effects on cumulative FE and LB moments were most substantial qualitatively and quantitatively (Figure 2.5). Experienced workers had lower cumulative FE moments during symmetric vs. asymmetric tasks, while the opposite occurred among novices. Both experienced and novice workers had similar cumulative LB moments during symmetric tasks, whereas novices had higher values than experienced workers during asymmetric tasks.

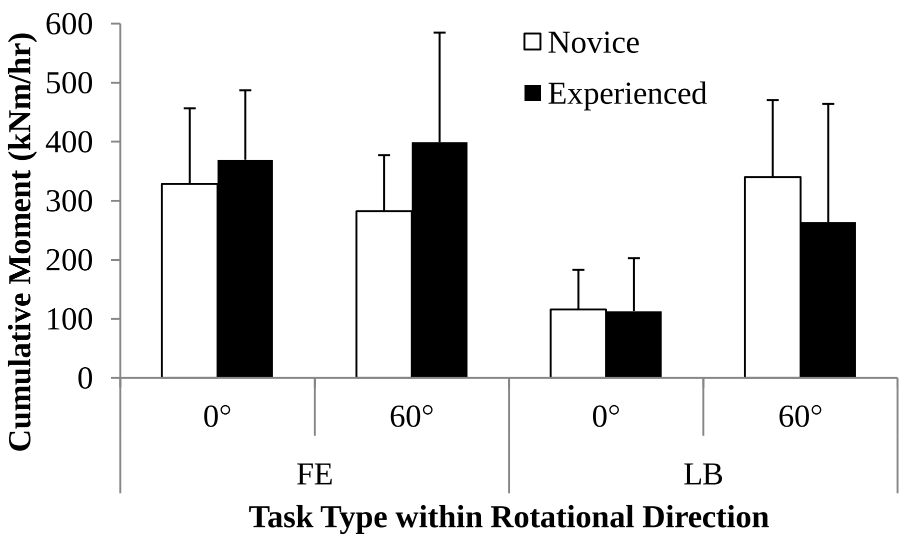

Figure 2.5. Mean values of cumulative lumbar moments (FE = flexion/extension; LB = lateral bending) in different task conditions (0° = symmetric lift/lower vs. 60° = asymmetric lift/lower). Errors bars indicate SDs.

2.3.4. Timing of peak values

There were significant differences between experienced and novice workers in the timing of peak values for several measures during both lifts and lowers (Table 2.5). For lifts, differences in the timing of peak kinematics were relatively small (~5-10% of lifting duration). More substantial differences were evident for peak lumbar moments. Among the experienced workers, FE moments occurred earlier in the lift (10 vs. 31% of lifting duration) and LB moments occurred later (61 vs. 36% of lifting duration). For lowers, differences in timing of peak lumbar angles and angular velocities were also relatively small between groups. Peak LB angular accelerations occurred later in the experienced worker group (91 vs. 69% of lower duration) as did peak FE moments (61 vs. 36% of lower duration).

Table 2.5. Timing of peak values (% of lift or lower duration). Values are means (SD), with bold values indicating cases where differences between the two groups were significant ($p < 0.05$).

		Lift		Lower	
		Experienced	Novice	Experienced	Novice
Peak lumbar angle	FE	**5.5 (8.6)**	**0.3 (1.4)**	**93.3 (11.6)**	**99.0 (1.5)**
	LB	50.8 (39.8)	55.8 (37.9)	46.7 (38.7)	40.0 (40.6)
	TW	76.0 (30.6)	72.5 (32.8)	**32.2 (37.4)**	**20.1 (27.9)**
Peak lumbar angular vel.	FE	**41.3 (7.1)**	**36.3 (5.4)**	55.8 (8.2)	57.4 (10.4)
	LB	49.0 (30.5)	46.7 (24.6)	**42.7 (27.7)**	**35.8 (28.6)**
	TW	51.6 (18.1)	49.6 (24.6)	**44.4 (20.6)**	**32.5 (18.8)**
Peak lumbar angular acc.	FE	**46.2 (19.6)**	**54.0 (6.1)**	**52.6 (28.5)**	**36.2 (25.0)**
	LB	**37.2 (23.8)**	**43.6 (19.2)**	**56.0 (26.2)**	**36.2 (25.0)**
	TW	50.6 (23.6)	51.2 (26.2)	42.0 (26.2)	37.9 (22.2)
Peak lumbar moment	FE	**10.2 (14.3)**	**30.7 (35.8)**	**91.4 (8.1)**	**68.8 (33.1)**
	LB	**60.7 (26.9)**	**35.5 (27.1)**	46.6 (26.5)	50.1 (27.7)
	TW	26.3 (27.2)	24.5 (25.2)	68.8 (28.9)	62.0 (30.1)

2.3.5. Variability

Within- and between-participant VCs were higher among experienced workers for most measures (Table 2.6). Specifically, experienced workers exhibited higher within-participant VC and larger differences were found in peak FE angles, LB angular velocities, LB/TW accelerations, LB moments, and cumulative FE moments. Between-subject variability within the experienced worker group was also consistently higher than within the novices; this was true for all measures, with the most substantial differences evident for triaxial lumbar angular velocities, accelerations, and moments.

Table 2.6. Summary measures of within- and between-participant variability in the Experienced and Novice groups. Values are presented as variance components (s^2).

		Within		Between	
		Experienced	Novice	Experienced	Novice
Peak lumbar angle (deg)	FE	17.9	8.4	153.4	121.2
	LB	4.8	3.5	2.8	1.6
	TW	84.1	79.4	16.9	0.0
Peak lumbar angular vel. (deg/s)	FE	76.9	60.0	211.2	49.1
	LB	20.0	8.6	7.9	1.9
	TW	304.6	230.7	47.0	0.5
Peak lumbar angular acc. (deg/s^2)	FE	1715.0	1118.5	5978.3	571.7
	LB	689.8	152.8	367.9	24.1
	TW	3119.4	1723.4	1023.8	58.5
Peak lumbar moment (Nm)	FE	404.7	243.7	902.2	303.9
	LB	2159.8	1127.9	1917.0	486.4
	TW	60.1	42.6	237.5	56.4
Cumulative lumbar moment (Nm/hr)	FE	7446.1	3494.1	20103.0	11483.9
	LB	12555.5	16592.9	20471.6	8090.0
	TW	455.7	336.8	1431.4	690.8

2.4. Discussion

Experienced workers in the current study consistently adopted lifting/lowering methods using higher torso kinematics and kinetics. More specifically, experienced workers had significantly higher peak lumbar FE/LB accelerations and peak FE moments. While not significant, peak FE angles and velocities were also higher among experienced workers, and these differences were relatively large. Particularly for torso flexion/extension, at least within the current experimental setting, the methods adopted by experienced workers involved a wider range of motion, faster speed, higher accelerations, and higher torque. Thus, and agreeing with our first hypothesis, the behaviors of experienced workers appear to result in higher levels of exposure to WRLBD risks during repetitive lifting/lowering tasks.

In contrast to our results, several earlier studies using similar measures (Granata *et al.* 1999, Marras *et al.* 2006, Patterson *et al.* 1986, Plamondon *et al.* 2010) concluded that the work methods of experienced workers were protective (i.e., associated with lower risk of WRLBDs). While true overall, specific results from these are inconsistent with respect to some measures of torso kinematics and kinetics. Patterson *et al*. (1986) found lower lumbar moments among experienced lifters, which could be considered beneficial for preventing WRLBDs. Conversely, Granata *et al*. (1999) reported that experienced workers exhibited higher lumbar moments and higher torso muscle co-contraction levels (that may increase torso muscle stiffness and thereby reduce injury risk), as well as reduced torso kinematics. Plamondon *et al*. (2010) found comparable torso moments and higher torso angular velocities among experienced workers. Collectively, it does not appear that experienced workers consistently control torso kinematics and kinetics to reduce WRLBD risks.

Another major finding was that torso kinematics and kinetics changed between task configurations, specifically for symmetric vs. asymmetric tasks and lifts vs. lowers. As evident from several significant or marginal interactive effects on torso kinematics and kinetics, experienced workers demonstrated such changes whereas novices adopted relatively consistent work methods. In addition, experienced workers had lower cumulative FE moments during symmetric vs. asymmetric tasks while novices displayed the opposite pattern. Therefore, in support of our second hypothesis, the methods used by experienced workers were task-dependent and distinct from that of novices. Although task configurations vary in existing reports, this latter finding is generally consistent with earlier evidence (Marras *et al.* 2006, Plamondon *et al.* 2010).

In the present study, the higher initial foot distance (D) used by experienced workers implies that they may not focus on peak torso kinematic and kinetics associated with WRLBD risks, particularly since the observed differences in torso biomechanics may be a direct consequence of differences in initial postures. More specifically, the experienced workers had substantially (~65.3Nm) higher peak FE moment during lifting, and these peak moments occurred earlier during a lifting task (~10% of the duration vs. ~30% for novices). From additional analyses, this difference in timing yielded differences in torso postures, torso accelerations, and linear box accelerations that accounted for respective differences of ~18.1Nm (~27.7%), ~20.1Nm (~30.8%), and ~8.4Nm (~12.9%) in peak

FE moment. Experienced workers thus adopted higher torso accelerations near lifting initiation, suggesting distinct lifting strategies in the current study. Additional analyses also indicated that lift/lower durations of experienced vs. novice workers were 1.39 (0.25) vs. 1.66 (0.25) sec., respectively. It thus appears that the experienced workers adopted relatively faster lifting strategies, using higher accelerations at lift/lower initiation. Such strategies have been considered to involve more risk of lower back injury (Granata and Marras 1995, Lavender *et al.* 2003), though faster lifts might also increase the period of time available for tissue recovery or reduce net work (Delisle *et al.* 1996). Overall, the specific risks imposed by slower vs. faster lifting strategies are currently unclear (Lin *et al.* 1999).

Of note, though, the experimental tasks involved relatively low risks associated with the use of a light box mass (10% of participant's body mass). In this case, experienced workers may presume a low risk of WRLBDs based on prior experience or may perhaps try to increase work efficiency, whereas novices may have avoided low back loading. Most existing studies did not report box position relative to the lumbar spine. As an exception, and in contrast to our results, Plamondon *et al.* (2010) found closer vertical and horizontal box positions among experienced workers though with comparable lumbar moments between experienced and novice workers. Differences in task configurations can account for some of the discrepancies between studies, since work method modifications with different task configurations were evident, especially for experienced workers (Authier *et al.* 1996, Marras *et al.* 2006, Patterson *et al.* 1986). Potential confounding effects are also present in earlier studies, which did not consistently control for important variables including age, anthropometry, and/or strength, though such effects appear unlikely here (*cf*. Table 2.1).

Larger within-subject variability (i.e., across multiple lifts/lowers) was evident in most kinematic and kinetic measures among the experienced workers. This may reflect the use of a larger number of degree-of-freedom in the kinematic chain or the use of a more flexible motor control strategy (Newell and Vaillancourt 2001). The larger within-subject variability among experienced workers is also generally consistent with earlier findings (Granata *et al.* 1999, Madeleine *et al.* 2008). Larger between-subject variability was also evident among the experienced workers. This may as well indicate that experienced workers used more flexible lift/lower strategies, here reflecting individual adaptations to the tasks.

The current findings may be limited to specific task configurations as discussed above. Several other potential limitations should also be noted. First, experienced workers recruited here possibly possessed or acquired lifting/lowering methods appropriate for specific goals in a specific variety of jobs. Thus, experienced workers may not have been completely familiar with the current experimental setting, though practice was provided before data collection. Future work may thus benefit from recruiting workers with substantial experience specific to the task configurations being investigated. Novices here were also limited to those with no experience in jobs involving lifting/lowering, yet daily lifting activities or personal fitness status were not controlled. Second, the small sample size may not fully represent either of the experienced or novice groups. However, it did allow for detecting group-level differences in torso kinematics and kinetics as in existing studies (Authier *et al.* 1996, Granata *et al.* 1999). Further, as estimated from our results and Granata *et al.* (1999), effect sizes related to group-level differences appear relatively large, though again the current groups may not be fully representative due to the small sample size. Third, asymmetrical testing was limited to the right side, though it seems unlikely that the current major results would be substantially different depending on the direction of asymmetry. Fourth, the current results describe relatively short-term behaviors under controlled condition, specifically repetitive lifts and lowers over about two minutes. The level of generalizability to typical working conditions, of longer duration and more varied work situation, is unknown. Fifth, although experienced workers exhibited higher levels of exposures, the overall risk levels appeared moderate. Quantifying differences in the magnitudes of actual risks are also difficult, given limitations in existing risk assessment methods and potential individual differences (e.g., in tissue tolerance) that could not be determined here.

In this study, WRLBD risks associated with experience were assessed using several biomechanical measures in a range of simulated material handling tasks. Work methods adopted by experienced workers appeared to involve higher low back injury risks, and a substantial level of task-dependency. Inconsistencies in the evidence regarding torso kinematics and kinetics suggest that minimizing these may not be the primary purpose of motor control strategies employed by experienced workers. Instead, experienced workers may adopt work methods, perhaps contingent on the specific task, to achieve goals unrevealed in the current study. For example, experienced workers may use work methods to enhance balance and movement stability, or decrease strength demands and energy expenditure, at the expense of torso kinematics and kinetics. Finally, this and earlier work suggests that work methods used by experienced workers may not serve as a consistently effective model for training that aims to reduce WRLBDs related to manual materials handling tasks. While there may be benefits to such an approach, such benefits are probably highly dependent on specific task demands.

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Chapter 3: Experienced workers may sacrifice peak torso kinematics/kinetics for enhanced balance/stability during repetitive lifting

Abstract

Work-related low back disorders (WRLBDs) are widely recognized problems, and work experience, while often considered important, has an unclear role with respect to modifying WRLBD risks. For example, some studies have shown that peak torso kinematics/kinetics are higher among experienced workers, suggesting a counterintuitive higher risk. To better understand the movement strategies of experienced workers, additional analyses were conducted using data from a prior study, to assess whole body balance and torso movement stability of six experienced workers vs. six novices during repetitive lifts/lowers. Dynamic balance and torso movement stability were quantified using peak linear/angular momenta and largest Lyapunov exponent (LLE) of torso flexion/extension, respectively. Peak horizontal linear momenta, all angular momenta, and LLEs were lower among experienced workers, suggestive of superior balance maintenance and more stable torso flexion/extension. Thus, experienced workers seem to sacrifice peak torso kinematics/kinetics to obtain better balance maintenance and torso movement stability, whereas the opposite strategies were evident among novices. This findings highlight that movement strategies can be modified by work experience and have potential implications/applications for worker training or work method analyses.

Keywords: experience; lifting; balance; stability; biomechanics

3.1. Introduction

Work-related low back disorders (WRLBDs) are widely recognized problems (Deyo *et al.* 2009, Hoy *et al.* 2010, Tak and Calvert 2011), and manual material handing (MMH) tasks appear to be a substantial risk factor (Dempsey 1998, Kuiper *et al.* 1999, NIOSH 1997). Work experience specific to MMH is considered a potential factor modifying WRLBD risks (Marras 2000), though the specific contribution of work experience to WRLBDs is presently unclear. For example, among existing studies that have assessed the work methods adopted by experienced workers vs. novices during MMH tasks (Authier *et al.* 1996, Gagnon 1997, Granata *et al.* 1999, Gregory *et al.* 2006, Lee and Nussbaum 2012, Marras *et al.* 2006, Pal *et al.* 2010, Plamondon *et al.* 2010, Plamondon *et al.* 2012), mixed results have been described for torso kinematics/kinetics (for review, see Lee and Nussbaum, 2012). Particularly, some of these studies indicated that experienced workers used methods associated with higher levels of kinematic/kinetic demands on the lumbar trunk, and which can be interpreted as imposing a higher level of risk. Experienced workers may thus not aim directly to reduce the magnitude of lumbar kinematics/kinetics (or, at least not do so consistently). Instead, alternative goals may exist, with the focus here on balance on stability.

Human balance often refers to postural adjustments to avoid falling (Winter 1995), and movement stability represents sensitivity to small perturbations (Kantz and Schreiber 2004). Balance and movement stability may be closely related to musculoskeletal control or movement strategies (Frank and Earl 1990, Graham *et al.* 2011, Granata and England 2006, Horak *et al.* 1997, Kang and Dingwell 2009). Particularly in balance maintenance, the role of an anticipatory movement strategy is considered important (Pavol and Pai 2002, Toussaint *et al.* 1997). This "pre-programmed" or anticipatory control seems closely related to prior experience (Do *et al.* 1991), and balance can be improved with training or experience (Chapman *et al.* 2008, Gautier *et al.* 2008, Lord *et al.* 1996, Min *et al.* 2012, Patton *et al.* 2000). Also, postural adjustments or balance influences movement trajectories and vice versa (Frank and Earl 1990). Thus, movement stability, which is often estimated from movement trajectories, may be highly related to experience. Despite such potential importance, existing studies investigating the movement strategy associated with work experience have rarely focused on balance or stability. The current study hypothesizes that experienced workers will exhibit better balance maintenance and torso movement stability. Investigating these additional measures may facilitate a better understanding of experienced worker's movement strategies.

3.2. Methods

3.2.1. Participants and procedures

Experimental data were obtained from prior work (Lee and Nussbaum 2012). Six experienced workers (body mass = 72.7(10.2)kg; stature = 1.79(0.09)m) and six novices (70.8(9.7)kg; 1.73(0.06)m) completed the study, with five males and one female in each group. All experienced workers reported ≥ 3 years of recent experience in "frequent lifting tasks", defined as lifting/lowering tasks performed ≥ 10 hours per week (*cf.* Patterson *et al.* 1986). Novices had no such experience and the two groups were individually age-matched (± one year). All participants completed informed consent procedures approved by the Virginia Tech Institutional Review Board (Appendices A and

B). There were no significant or substantial differences between the two groups in age, anthropometry, or lumbar isokinetic extensor strength.

After strength testing and a rest period (~30 min), each participant completed a set of lifting/lowering tasks in each of two asymmetry conditions (0° symmetric vs. 60° asymmetric; Figure 3.1) with a counterbalanced exposure order. In each set, participants repetitively (20 times) lifted/lowered a box with cut-out handles. Box mass was set to 10% of individual body mass, with mean(SD) masses of 7.3(1.0) and 7.3(1.0)kg) for the novices and experienced workers, respectively. The rate was controlled at 10 lift/lower cycles per minute, using a metronome, and throughout each set the participant continuously held the box. Lifting origin/destination heights were adjusted to individual knee/elbow height, foot positions were fixed, and a free-style lifting technique was used.

Figure 3.1. Task configurations using during symmetric (left) and asymmetric lifts/lowers (right).

Whole body motions were tracked, using surface markers, at 100Hz with a 7-camera system (Vicon Motion System, CA, USA). Motion data were low-pass filtered (bi-directional, 2nd-order, Butterworth, 5 Hz cutoff), and only the last 15 lifts/lowers were further analyzed.

3.2.2. Dependent measures

A 3D, linked-segment model with 15 body segments (and a box) was used, with body segment parameters based on Dumas et al. (2007). Segmental kinematics were derived as described by Winter (2004a). Whole body balance was assessed using peak values of linear (L) and angular momenta (H) as in Toussaint et al. (1995); these peak values were derived within each lift and lower using:

$$L = \sum_{k=1}^{N} \left(m_k \{\dot{p}_k\} \right) \tag{2}$$

$$H = \sum_{k=1}^{N} \Big([J_k]\{\dot{\theta}_k\} + m_k\{p_k\} \times \{\dot{p}_k\} \Big) \tag{3}$$

where k indexes body segments and the box, N is the total number of body segments and the box, m_k is the *k*-th segment mass, $\{\dot{p}_k\}$ is the linear velocity of the *k*-th segment COM, $[J_k]$ is the moment-of-inertia of the *k*-th body segments relative to its COM, and $\{\dot{\theta}_k\}$ is the angular velocity of the *k*-th segment COM. Momenta were normalized and converted to the original units using:

$$L_n = (\mu_m \times \mu_h) \times \frac{L}{m \times h} \tag{4}$$

$$H_n = (\mu_m \times \mu_h^2) \times \frac{H}{m \times h^2} \tag{5}$$

where *m* and *h* are the body mass and the stature of a participant, respectively, and μ_m and

μ_h are the mean participant body mass and stature, respectively. All peak momenta were calculated from absolute values with respect to a global coordinate system (+X = right, +Y = anterior, +Z = superior). During dynamic tasks such as lifts/lowers, linear and angular momenta are considered highly related to balance maintenance, particularly in terms of anticipatory postural adjustment schemes (Heiss *et al.* 2001, Pai and Lee 1994, Toussaint *et al.* 1995).

Torso movement stability was quantified using largest Lyapunov exponents (LLEs) of torso flexion/extension angle time series. Initially, a state-space was reconstructed using a delay-coordinate method (Dingwell *et al.* 2001). Specifically, time delays and embedding dimensions were estimated, respectively using average-mutual-information (Fraser and Swinney 1986) and false-nearest-neighbors methods (Kennel *et al.* 1992). From the reconstructed state-space, the LLEs were estimated using the algorithm of Rosenstein et al. (1993). These were done using the TISEAN software package (Hegger and Kantz 1999) with the same number of data points (9,000). From the resulting logged distance plot (LDP), which illustrates log-scaled Euclidean distances between a set of nearest data points in a state-space over time, the slope (LLE) was determined. An initial linear region was first identified from each LDP, and the LLE was then estimated using linear regression over this region (Hegger and Kantz 1999).

3.2.3. Statistical analysis

Three-way, mixed-factor analyses-of-variance (ANOVAs) were used to assess the effects of experience (E), task asymmetry (A), and lift/lower (L) on peak momenta. Two-way

ANOVAs were used for the effects of E and A on LLEs. Statistical analyses were performed using JMP™ (v9, SAS Institute, USA), with significance concluded when $p <$ 0.05. Significant interaction effects were explored using pairwise comparisons (Tukey's HSD). Summary results are given as means(SD). Given the study aims, the results focus on main and interactive effects of experience.

3.3. Results

Peak linear momenta in the Y and Z directions were significantly higher overall in the novice and experienced groups, respectively, though these main effects were overshadowed by interactive effects with asymmetry that were significant in all three directions (Table 3.1). During symmetric lifts/lowers, experienced workers had comparable values in the X and Y directions and significantly higher values in the Z direction (Figure 3.2). During asymmetric lifts/lowers, novices had higher values in all three directions. Although significant E×A×L interactive effects were found, the E×A interaction effects were qualitatively similar for both lifts and lowers. All peak angular momenta were significantly higher among novices, and with interactive effects similar to those described for linear momenta (Table 3.1). Differences between novices and experienced workers again varied depending on the axis and level of asymmetry (Figure 3.3). Angular momenta about all three axes were comparable between groups during symmetric lifts/lowers, and consistently higher among novices during asymmetric lifts/lowers.

Table 3.1. ANOVA results (p-values) for main and interactive effects of experience (E), asymmetry (A), and lift vs. lower (L). Values shown in bold are significant ($p < 0.05$).

		E	E×A	E×L	E×A×L
Peak linear momentum	X	0.31	**<0.0001**	0.23	**0.0057**
	Y	**0.0055**	**<0.0001**	0.93	**0.0014**
	Z	**0.015**	**<0.0001**	0.14	0.95
Peak angular momentum	X	**0.020**	**<0.0001**	0.83	**0.0071**
	Y	**0.0015**	**<0.0001**	0.51	**0.0010**
	Z	**0.021**	**<0.0001**	0.42	0.084

Direction/Axis: X = medial/lateral; Y = anterior/posterior; Z = superior/inferior

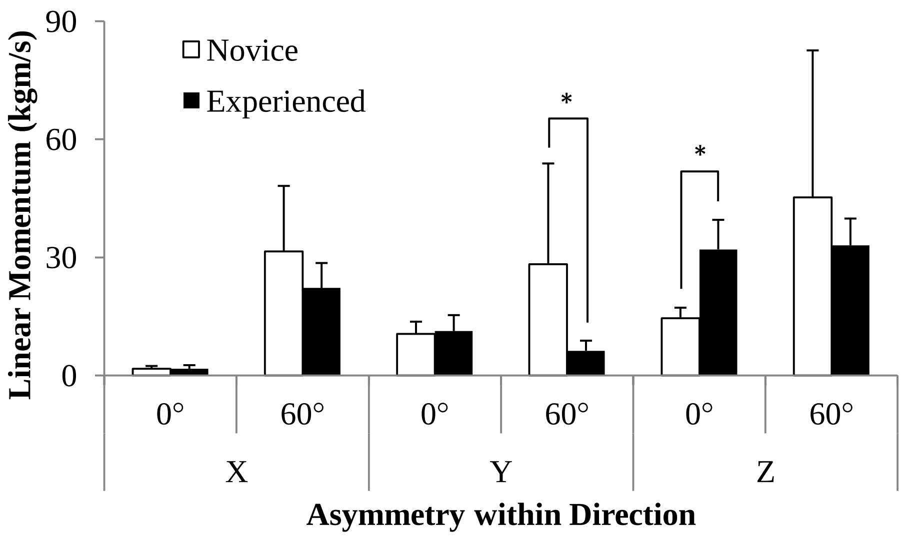

Figure 3.2. Mean values of peak linear momenta (+X = right; +Y = anterior; +Z = superior) during lifting/lowering in the two asymmetry conditions (0° = symmetric vs. 60° = asymmetric). The symbol * indicates a significant difference between novice and experienced workers, and error bars indicate SDs.

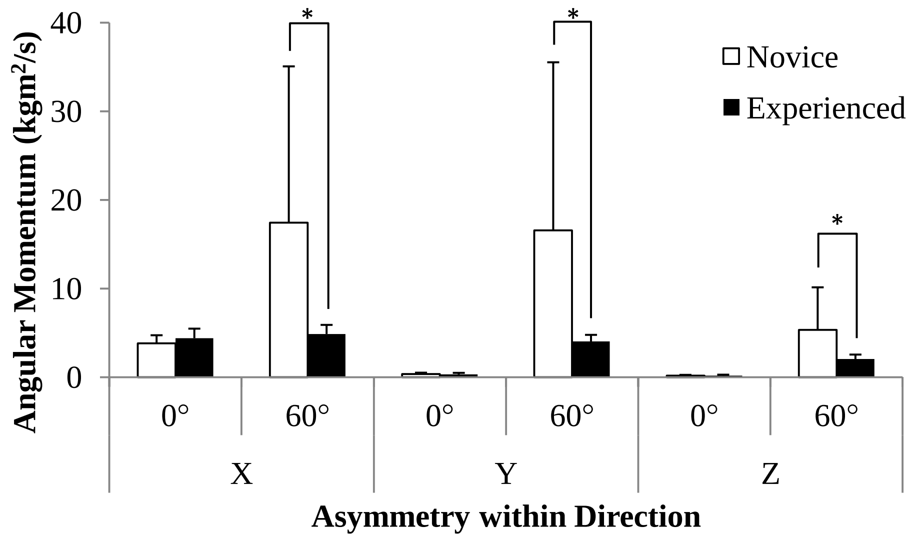

Figure 3.3. Mean values of peak angular momenta (+X = right; +Y = anterior; +Z = superior) during lifting/lowering in the two asymmetry conditions (0° = symmetric vs. 60° = asymmetric). The symbol * indicates a significant difference between novice and experienced workers, and error bars indicate SDs.

LLEs for torso flexion/extension were significantly (p = 0.011) lower among experienced workers. There was also a significant (p = 0.010) E×A interaction effect, wherein the difference between groups was more evident during symmetric vs. asymmetric lifting/lowering (Figure 3.4). Mean time delay and embedding dimension were 1.42(0.12)s and 4.38(0.82), respectively. Main effects of group were not significant for time delay (novice = 1.41(0.12)s vs. experienced = 1.42(0.12)s; p = 0.91) or embedding dimension (novice = 4.1(0.67) vs. experienced = 4.7(0.89); p = 0.14). There was a significant (p = 0.03) E×A interaction effect on embedding dimension; torso movements for experienced workers had lower embedding dimensions for asymmetric vs. symmetric lifts/lowers, whereas the opposite was found among novices.

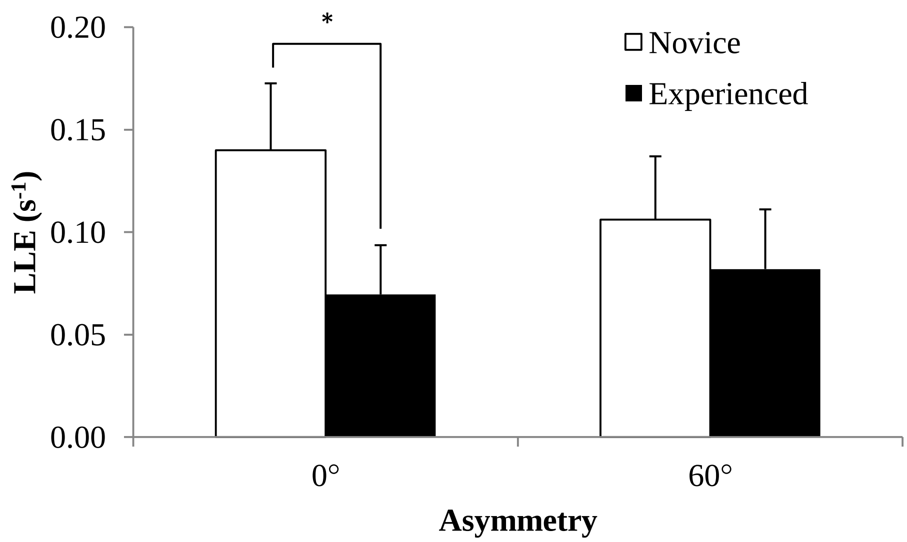

Figure 3.4. Largest Lyapunov Exponent (LLE) determined from torso flexion/extension angles during lifting/lower in the two asymmetry conditions (0° = symmetric vs. 60° = asymmetric). The symbol * indicates a significant difference between novice and experienced workers, and error bars indicate SDs.

3.4. Discussion

As context for the current results, primary findings in a previous analysis of kinematics and kinetics (Lee and Nussbaum 2012) are briefly reviewed. First, experienced workers overall completed symmetric and asymmetric lifting with higher peak torso kinematics/kinetics (angles, velocities, accelerations, and moments), similar to results in Plamondon et al. (2010) for torso velocities and Granata et al. (1999) for torso moments. Second, torso kinematics/kinetics among experienced workers were modified between tasks, but were relatively more consistent among novices, similar to findings in other studies (Marras *et al.* 2006, Plamondon *et al.* 2010). From such results, it was concluded that experienced workers may not consistently seek to minimize torso kinematics/kinetics during lifting/lowering tasks. Rather, this earlier analysis suggested that there might be alternative goals for developing movement strategies among such workers.

The present analysis suggests that differences in balance and torso movement stability are also present between experienced and novice workers during repetitive lifts/lowers. Experienced workers consistently exhibited superior postural adjustments and torso flexion/extension stability. More specifically, momenta that appear most directly related to balance (i.e., horizontal linear and angular momenta) were lower among experienced workers, and which suggests better balance-maintenance strategies. LLEs for torso flexion/extension were also lower among experienced workers, indicating that the torso movements were less sensitive to small perturbations and thus controlled by more stable strategies. This result of superior balance among experienced workers is consistent with earlier reports (Lord *et al.* 1996, Min *et al.* 2012, Patton *et al.* 2000). In contrast, evidence related to torso movement stability of experienced workers is limited (nonexistent, to the authors' knowledge).

Balance maintenance and torso movement stability among novices were highly dependent on task conditions (asymmetry), and a similar pattern of task dependency was reported earlier (Granata & England, 2006). In contrast, experienced workers maintained relatively consistent balance and stability across different task conditions. Experienced workers seemed to adjust torso kinematics/kinetics to maintain stable balance and torso movement, whereas novices may have de-emphasized balance and stability to obtain relatively consistent torso kinematic/kinetic exposures across different task conditions.

Thus, and in support of our hypothesis, experienced workers appear to adopt work methods to enhance whole body balance and torso movement stability at the expense of lumbar kinematics/kinetics.

The range of momenta and torso LLEs reported here are comparable with earlier reports (*cf*. Commissaris and Toussaint 1997, Graham *et al.* 2012, Heiss *et al.* 2001, Reisman *et al.* 2002). As in our original study (Lee and Nussbaum 2012), however, there are potential limitations in this work related to participant recruitment, the small sample size, measurements of only short-term behaviors, and use of only two specific task configurations. Other potential limitations should also be noted. First, momenta might not fully represent balance, since this construct can be assessed using a variety of other measures (e.g., using parameters derived from center-of-pressure or center-of-mass kinematics). Second, torso movement stability was analyzed only for flexion/extension motions.

In summary, we investigated differences in whole body balance and torso flexion/extension stability between experienced and novice workers. Incorporating prior analyses (Lee and Nussbaum 2012), movement strategies used by experienced workers may place more emphasis on maintaining whole body balance and torso movement stability vs. reducing peak torso kinematics/kinetics, whereas novices may focus more on peak torso kinematics/kinetics. While such findings may be contingent on specific task demands or configurations, they do begin to provide a better understanding of movement strategies associated with work experience. Such differences associated with experience may have implications/applications for the analysis of occupational tasks and worker training.

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Chapter 4: Effects of experience on fatigue-induced biomechanical changes during repetitive asymmetric lifts/lowers

Abstract

Repetitive, asymmetric lifting/lowering is associated with an increased risk of work-related low back disorders (WRLBDs), and this risk may be increased with fatigue. Work methods used by experienced workers are potential models for developing worker training to reduce WRLBDs, though whether experience modifies the effects of fatigue is largely unknown. Six experienced and six novice workers completed repetitive asymmetric lifts and lowers over extended periods (185 lift/lower cycles at 15 cycles per minute). Box mass was set to 15% of individual body mass, and several important confounding factors were controlled. Multiple measures were obtained to address WRLBD and/or fall risks: torso kinematics, torso kinetics, balance, and torso movement stability. Fatigue-induced changes were significant for most measures, which suggests altered movement strategies with fatigue. Although the overall effects of fatigue on risks for WRLBDs were unclear, due to opposite changes between peak torso kinematics and kinetics, fatigue decreased balance maintenance capability. Novices decreased peak lumbar moments post-fatigue, whereas they increased among experienced workers, suggestive of lower risks for WRLBDs among novices. Other than lumbar moments, fatigue substantially reduced group-level differences in lifting methods and behaviors. Further work is needed to determine if the movement strategies of experienced workers are an appropriate training model for reducing WRLBD risks.

Keywords: experience; low back; fatigue; repetitive lifting; biomechanics

4.1. Introduction

Work-related low back disorders (WRLBDs) remain important contemporary concerns, and continue to have a high prevalence, frequent recurrence, and substantial associated costs (Costa-Black *et al.* 2010, Leigh *et al.* 2006b, Woolf and Pfleger 2003). Among a variety of occupational tasks, asymmetric lifting or lowering has been considered an important risk factor for WRLBDs (Cole and Grimshaw 2003, Hoogendoorn *et al.* 2000, Marras *et al.* 1995). In addition, frequent muscle contractions or repetitive motions often cause localized muscle fatigue (LMF), which may also be a potential risk factor for WRLBDs (Swaen *et al.* 2003).

LMF refers to an acute impairment of muscle capacity, often quantified as a decrease in peak force or power generation. Specifically regarding aspects of muscular function, LMF involves reductions in recruited motor neuron discharge rates, maximum sustained force magnitudes, and muscle contraction/relaxation speeds (Allen *et al.* 2008). Neurophysiologically, LMF induces changes in both central and peripheral nervous system activities, referred to as motor adaptation, and likely due to altered muscle function and feedback/reflex inputs (Bonnard *et al.* 1994, Gandevis 2001). Regarding biomechanical aspects, such motor adaptation often results in modifications of joint kinematics (i.e., angle, velocity, acceleration, etc.) and joint kinetics (i.e., force, torque, etc.), and can also increase the variability of these measures and compromise balance maintenance (Janssen *et al.* 2002, Nardone *et al.* 1997, Paillard 2012, Srinivasan and Mathiassen 2012). These changes with LMF suggest the potential for elevated WRLBD risks, due to reduced muscle performance, a need for altered (i.e., atypical) motor control schemes, and inferior balance maintenance capability.

Repetitive torso flexions/extensions during manual material handling are of emphasis here, given the evidence for WRLBD risk noted earlier and since fatigue effects are task-dependent (Enoke and Stuart 1992). In repetitive lifting/lowering, specific mechanisms by which fatigue may contribute to increased WRLBD risk are unclear, given the divergence in existing evidence. Specifically during repetitive, symmetric lifts/lowers, fatigue has been found to both increase (Trafimow *et al.* 1993) and decrease (van Dieën *et al.* 1998) mean torso angular velocities, as well as lead to and higher (Bonato *et al.* 2003) and lower (Dolan and Adams 1998) peak lumbar moments. In contrast to this lack of consistency regarding fatigue effects on torso kinematics and kinetics, there is more consistent evidence that fatigue adversely affects balance maintenance capability in general (Paillard 2012) and specifically during lifting (Sparto *et al.* 1997). Torso movement stability was also reported to decrease with fatigue during repetitive, unloaded, symmetric torso flexions/extensions (Granata and Gottipati 2008).

Movement strategies adopted by experienced workers are often considered to result in lower risks for WRLBDs, and these strategies have been adopted to develop interventions aimed at reducing WRLBD risks (Gagnon 1997, 2003). For example, Authier et al. (1996) found that relatively distinct lifting techniques were used by experienced workers in transferring boxes (e.g., box tilting, grips, and knee/foot positions), and these techniques were tested and reported to reduce back loading (Gagnon 1997). Other earlier studies also concluded that, during relatively short periods, novice workers may use lifting or other work methods associated with higher injury risks (Granata *et al.* 1999, Gregory *et al.* 2006, Keir and MacDonell 2004, Madeleine *et al.* 2003, Pal *et al.* 2010, Patterson *et al.* 1986). However, mixed results regarding differences with experience have been found for peak torso kinematics and kinetics in terms of WRLBD risks. Specifically for torso flexion/extension, some studies have reported higher peak angles, angular velocities, and moments among experienced workers (Granata *et al.* 1999, Lee and Nussbaum 2012, Plamondon *et al.* 2010). Thus, the association between WRLBD risks and the work methods used by experienced workers is currently unclear.

Evidence is particularly lacking, and to our knowledge nonexistent, regarding whether the effects of LMF on work methods during repetitive lifting/lowering might differ with work experience. Determining whether such differences exist is considered important, especially if training programs are developed incorporating (or targeting) the work methods of experienced workers. In addition to understanding WRLBD risks and contributing to training development, understanding if and how experience modifies the effects of LMF can also help in understanding the specific roles or mechanisms of work experience. As described above, physiological changes with fatigue may lead to a need for unfamiliar or untrained neuromuscular control strategies, particularly ones that are not pre-programmed or lack feed-forward movement strategies. The acquisition of new motor control strategies is often referred to "motor plasticity" or "brain reorganization" (Boroojerdi *et al.* 2001), and which has some relevance to the effects of work experience. However, related evidence is quite limited, especially in terms of biomechanical aspects.

For example, experienced workers have reported lower perceived discomfort (Parakkat *et al.* 2007) and higher maximum acceptable weight limits (Mital 1987) during extended work periods, and post-fatigue differences in energy expenditure and biomechanical exposures have also been found with experience (Marras *et al.* 2006, Mital *et al.* 1994). These noted studies, however, only addressed post-fatigue fatigue differences, and not changes resulting from fatigue.

Given the important potential influence of fatigue-induced biomechanical changes, and modifying effects of work experience on such changes, the current study was designed to address two specific hypotheses. First, that fatigue will induce changes in torso kinematics/kinetics, whole balance, and torso movement stability during repetitive, asymmetric lifting/lowering. Second, that these effects of fatigue will differ with experience. Results were intended to help in developing/evaluating training programs incorporating movement strategies of experienced workers as a training model.

4.2. Methods

4.2.1. Participants

Six experienced and six novice workers completed the study, with five males and one female in each group (Table 4.1). Experienced workers were recruited based on the duration of work experience from among local delivery facilities, farms, stores, and warehouses. All reported a minimum of 2.5 yrs of recent work experience in "frequent lifting tasks", which were operationally defined as lifting/lowering tasks conducted for at least 10 hours per week on average, similar to our earlier work (Chapter 2). Novice workers were recruited from local students who had no experience in "frequent lifting tasks", and specific participants were selected so that two groups were age-matched (±two years) at the individual level. All participants reported no current or prior musculoskeletal disorders and completed informed consent procedures approved by the Virginia Tech Institutional Review Board (Appendices A and B).

4.2.2. Procedures

Isokinetic lumbar extensor strength was measured initially for each participant. Maximum voluntary concentric and eccentric contractions were performed, using a commercial dynamometer (Biodex System 3 pro, Biodex Medical Systems Inc., NY, USA) with a custom fixture to isolate the pelvis and lower extremities. After initial warm-up and rest, a minimum of five trials, interspersed with two-min rest breaks, were completed at 120°/s with a range of motion of 0° (upright) - 80° (torso flexion). These specific parameters were selected to enhance reliability (Keller *et al.* 2001) and to approximate the task demands during the lifting/lowering task examined.

After additional rest, each participant then completed a set of practice lifting tasks, involving 10 lift/lower cycles. A wooden box was used ($33\times59\times24$ cm^3), which had cut-out handles 21cm from the bottom and was loaded to equal 15% of individual body mass. The configuration of the environment was such that the box was moved from/to the front of the body and the destination was rotated 60° to the right (Figure 3.1). The horizontal distance from the midpoint of participant's ankles to the lifting origin/destination was kept constant (38 and 69 cm, respectively) across all participants. The vertical location of the box at the origin/destination was set so that the top of the box was at the participant's knee/elbow joints. A freestyle method was adopted for lifting/lowering, with no other specific instructions regarding work methods provided, as in earlier related studies (Marras *et al.* 2006, Plamondon *et al.* 2010). During these cycles, participants continuously held the box and the cycle frequency was 15/min, which was controlled using an electronic metronome.

Table 4.1. Participant information (means (SD)) and results of *t*-tests comparing the Experienced and Novice groups.

	Age (yrs)	Experience (yrs)	Stature (m)	Body Mass (kg)	Lumbar Extensor Strength (Nm)	
					Concentric	Eccentric
Experienced	28.3 (6.9)	7.4 (4.5)	1.73 (0.10)	86.6 (14.6)	311.8 (70.5)	357.3 (71.3)
Novice	26.8 (7.1)	0.0 (0.0)	1.80 (0.09)	80.2 (10.9)	316.8 (77.3)	372.2 (49.2)
Test result	$t = -0.37$ $p = 0.72$	- -	$t = 1.29$ $p = 0.23$	$t = -0.87$ $p = 0.41$	$t = 0.12$ $p = 0.91$	$t = 0.42$ $p = 0.68$

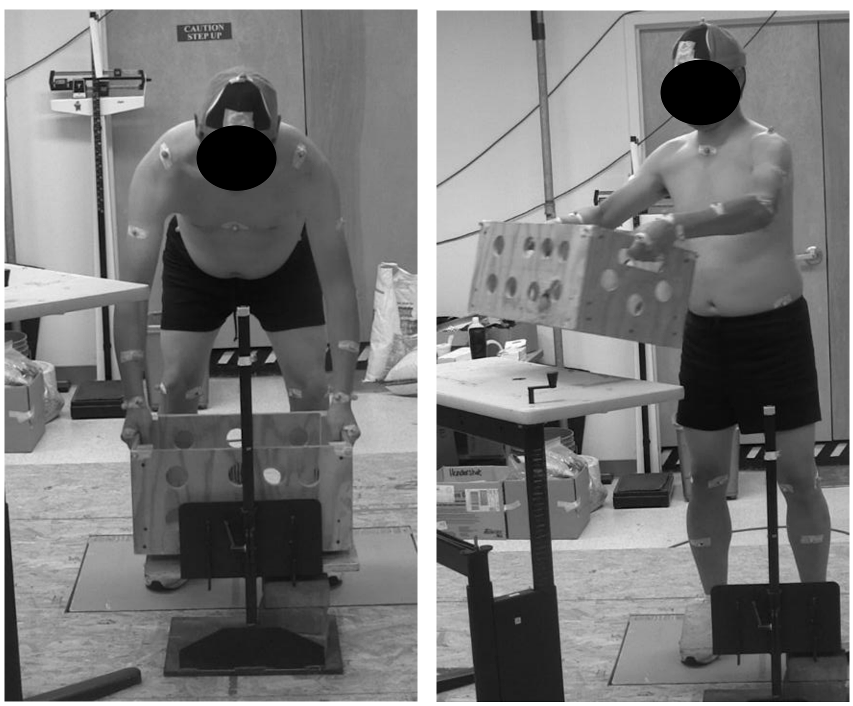

Figure 4.1. Task configuration using an adjustable workstation during asymmetric lifts/lowers.

After practice, rest was again provided, and then participants completed a set of 185 lift/lower cycles, using the same box, procedures, and configuration as in the practice trials. These specific conditions were selected based on pilot work, so that localized muscle fatigue (mostly at the low back and upper arms) was present at the end of the set.

4.2.3. Data collection and processing

Reflective markers were attached over anatomical landmarks as described by Dumas *et al.* (2007), and tracked at 100 Hz with a 7-camera system (Vicon Motion System Inc., CA, USA). To improve accuracy, additional markers were attached over relatively immobile body parts: vertebral process of T10 (torso), mid-way between bilateral posterior superior iliac spines (pelvis), the anterior borders of the tibias (shank), lateral mid-way between head vertex and occiput (head), mid-way between acromion and lateral humeral epicondyle (upper arm), and approximate mid-way between ulnar styloid and lateral humeral epicondyle (lower arm). Ground reaction forces and moments were measured using two force platforms (OR6-7-1000, AMTI, MA, USA), and sampled at 1000Hz. Motion and force data were low-pass-filtered (bi-directional, 2^{nd}-order Butterworth) with respective cut-off frequencies of 5 and 10 Hz, and force data were down-sampled to 100Hz. Initiation and termination times for each lifting and lowering event were identified using the vertical velocity of the box.

4.2.4. Dependent measures

Multiple measures were obtained to describe work methods, specifically addressing torso kinematics/kinetics, whole body balance, and torso movement stability. A 3D linked-segment model with 15 body segments (and a box) was developed, with segmental masses, inertial tensors, and center-of-mass (COM) locations based on scaling methods in Dumas et al. (2007). As these measures are described in detail elsewhere (Chapters 2 and 3), brief descriptions are provided here. Torso kinematics were derived using Euler angles about the +X (= right), +Y (=anterior), and +Z (=superior) axes, and with an XYZ rotation sequence. Peak triaxial torso angles, angular velocities, and angular accelerations were identified to describe torso kinematics (Winter 2004b), peak/cumulative triaxial L5S1 moments for torso kinetics (Kingma *et al.* 1998), linear/angular momenta for balance (Toussaint *et al.* 1995), and the largest Lyapunov exponent (LLE) for torso stability (Rosenstein *et al.* 1993). Moments and momenta were normalized to minimize the influence of anthropometric differences, and converted back to the original units by multiplying by mean stature and body mass across participants to facilitate comparisons with published values. Measures of momenta were calculated with respect to a global coordinate system and all other measures were based on segmental coordinate systems. All peak/cumulative measures were determined from absolute values. The initial five of the 185 cycles were excluded to minimize start-up effects. The first and last 30 cycles of the remaining cycles (180 cycles) were used to characterize pre-fatigue (or, low level of fatigue) and post-fatigue behaviors, respectively, and change scores (post - pre) were obtained for all measures. For each participant, these groups of 30 cycles for each condition yielded the same number of data points (1.2×10^4) for estimation of LLE. Additionally, the times at which peak values occurred were identified, and represented as percentages of the duration of a given lift or lower. Peak values were determined from absolute values of each dependent measure.

4.2.5. Statistical analysis

For each dependent variable, overall differences between pre- and post-fatigue conditions were assessed using paired *t*-tests. Potential modifying effects of experience and task (lift/lower) on fatigue-related effects (i.e., change scores = post-fatigue – pre-fatigue) were assessed using analyses of covariance (ANCOVAs). In these ANCOVAs, pre-fatigue values were used as a covariate, as were interactive effects of experience and pre-fatigue values (Dimitrov and Rumrill 2003). For stability measures, only the effects of experience were used in ANCOVAs since these were determined across lift/lowers. Statistical analyses were done using JMP TM (v9, SAS Institue Inc., NC, USA), with significance concluded when $p < 0.05$. The presentation of results focuses only on the effects of fatigue and group-level differences in these effects.

4.3. Results

No significant differences were evident between groups in terms of age, anthropometry, or lumbar extensor strength (Table 4.1). Fatigue-induced changes were significant for several dependent measures (Table 4.2). For several peak and cumulative lumbar moments, the fatigue effects significantly differed between groups, and a difference between lifts/lowers was evident for only a single measure. Fatigue-induced changes, for a range of dependent measures, were significantly associated with pre-fatigue values (covariates) and in a few cases this association differed between groups. The results are described in more detail below, separately for each category of dependent measure.

Table 4.2. Summary of the effects of fatigue on the dependent measures. Overall effects of fatigue, across groups and lifts/lowers are presented initially, including pre- and post-fatigue means (SD) and results from statistical comparisons (*p*-values). ANCOVA results (*p*-values) indicate whether fatigue effects differed between experience groups (E), between lifts and lowers (L), whether pre-fatigue (Pre) measures were a significant covariate, and whether this covariate effect differed between groups (E×Pre). Values shown in bold are significant ($p<0.05$), while those in italics approached significance ($0.05 \leq p \leq 0.07$).

		Overall Effect of Fatigue			ANCOVA				
		Pre-fatigue	Post-fatigue	Difference	E	L	E×L	Pre	E×Pre
Peak lumbar angle (deg)	FE	40.2(12.5)	46.4(9.5)	**0.0070**	0.63	0.57	0.66	**0.0008**	0.22
	LB	5.2(2.6)	6.0(1.9)	*0.067*	0.70	0.39	0.43	**0.0064**	0.68
	TW	20.6(4.6)	19.5(4.4)	0.25	0.36	0.22	0.99	**0.042**	0.13
Peak lumbar angular vel. (deg/s)	FE	43.1(15.4)	50.0(13.8)	**0.021**	0.84	0.82	0.35	**0.011**	0.67
	LB	11.0(3.5)	13.6(5.0)	**0.0073**	0.60	0.77	0.75	0.15	**0.035**
	TW	44.2(8.3)	40.3(8.1)	**0.046**	0.20	0.96	0.50	0.76	0.17
Peak lumbar angular acc. (deg/s^2)	FE	137.0(51.5)	164.2(53.1)	**0.0007**	0.85	0.62	0.53	*0.063*	0.12
	LB	57.6(21.6)	79.1(30.8)	**0.0003**	0.10	0.37	0.60	0.70	0.28
	TW	151.4(36.4)	144.9(35.4)	0.37	0.93	0.48	0.82	0.11	0.97
Peak lumbar moment (Nm)	FE	150.3(37.9)	148.2(38.7)	0.70	*0.052*	0.40	0.54	0.074	0.90
	LB	100.0(41.9)	95.9(45.4)	0.64	**0.0029**	0.67	0.18	**0.024**	**0.033**
	TW	25.5(18.9)	33.8(15.7)	**0.026**	**0.023**	0.67	0.88	0.47	*0.054*
Cum. lumbar moment (kNm/hr)	FE	277.2(77.5)	251.5(95.5)	**0.032**	0.18	0.23	0.42	0.37	0.27
	LB	158.5(62.1)	204.3(124.4)	**0.043**	**0.032**	0.60	0.46	0.61	0.074
	TW	43.2(24.6)	56.4(27.2)	**0.037**	**0.0092**	0.96	0.94	0.25	0.65
Peak linear momentum (kgm/s)	AP	11.2(3.1)	12.9(2.8)	**0.0034**	0.19	0.69	0.81	**0.011**	0.77
	ML	26.0(6.1)	30.8(7.5)	**0.0003**	0.45	0.71	0.83	0.33	0.73
	SI	28.0(9.9)	27.1(5.5)	0.61	0.78	0.090	0.78	**0.0007**	0.45
Peak angular momentum (kgm^2/s)	FE	7.8(2.6)	8.4(1.9)	0.29	0.67	**0.014**	0.81	**0.0017**	0.87
	LB	6.7(1.2)	6.4(1.4)	0.18	0.14	0.32	0.98	*0.053*	0.42
	TW	4.9(1.2)	4.6(1.4)	0.27	0.22	0.080	0.89	0.12	0.19
Largest Lyapunov exponent (/s)	FE	0.26(0.05)	0.27(0.06)	0.66	0.13	-	-	0.27	0.25
	LB	0.19(0.03)	0.19(0.04)	0.94	0.79	-	-	**0.0071**	0.26
	TW	0.24(0.04)	0.25(0.05)	0.73	0.97	-	-	0.15	0.32

FE = flexion/extension, LB = lateral bending, TW = twisting, AP = anterior/posterior, ML = medial/lateral, SI = superior/inferior

4.3.1. Kinematics

Peak flexion/extension (FE) torso angles significantly increased post-fatigue, by ~15%. Peak lateral bending (LB) angles also increased, again by ~15%, though this change only approached significance. Fatigue-induced changes in all three peak torso angles were significantly and inversely associated with pre-fatigue values (Figure 4.2). Peak torso angular velocities significantly increased post-fatigue in both FE (~16%) and LB (~24%), whereas peak twisting (TW) values decreased (~-9%). Changes in peak FE angular velocities were significantly associated with pre-fatigue values, with a pattern qualitatively similar to that for peak angles. For peak LB angular velocities, the association with pre-fatigue values differed substantially between groups (Figure 4.3), with the experienced group having a negative association and the novice group a weaker positive association. Peak FE and LB torso angular accelerations significantly increased post-fatigue (respectively by ~20% and ~37%). The association between pre-fatigue and fatigue-induced changes in FE accelerations approached significance, with a pattern qualitatively similar to that for peak angles.

4.3.2. Kinetics

Peak lumbar TW moments significantly increased post-fatigue (~33%). Fatigue-induced changes in peak LB moments were significantly and negatively associated with pre-fatigue values. Differences in fatigue effects on peak moments were found between groups, depending on the specific rotational directions (Figure 4.4). For both peak LB and TW moments, the associations between fatigue-induced changes and pre-fatigue values differed between experience groups (Figure 4.5).

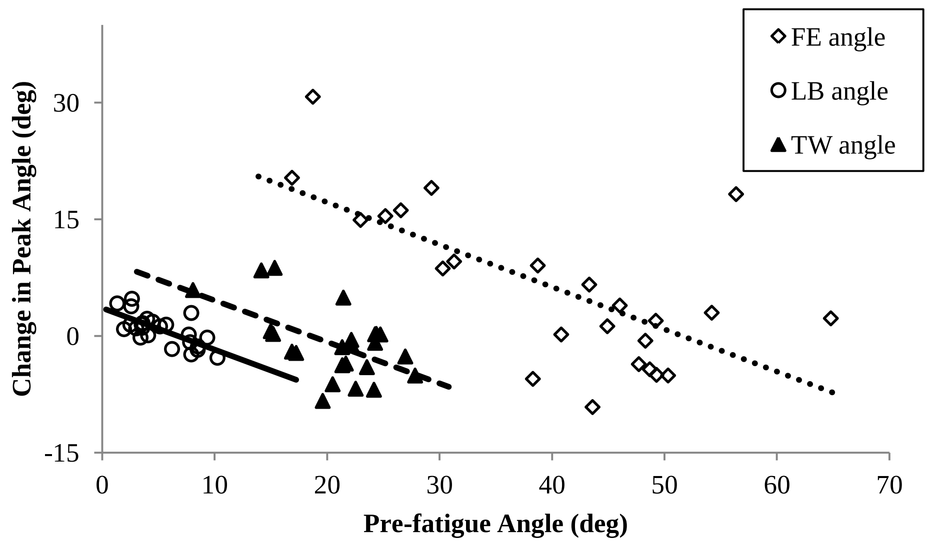

Figure 4.2. Linear associations between pre-fatigue peak torso angles and fatigue-induced changes in these angles (FE = flexion/extension; LB = lateral bending; TW = twisting).

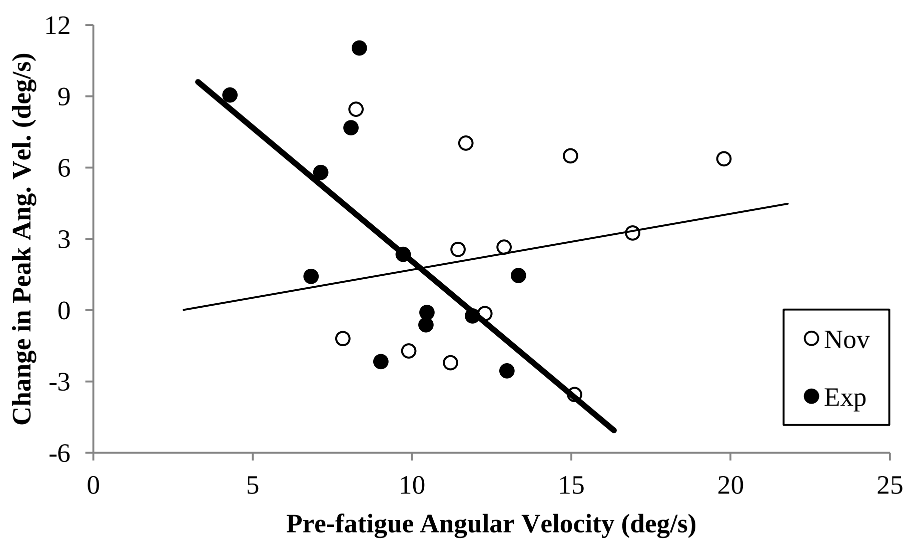

Figure 4.3. Group differences (Nov = novice; Exp = experienced) in the association between pre-fatigue peak torso angular velocities (lateral bending) and fatigue-induced changes in these velocities.

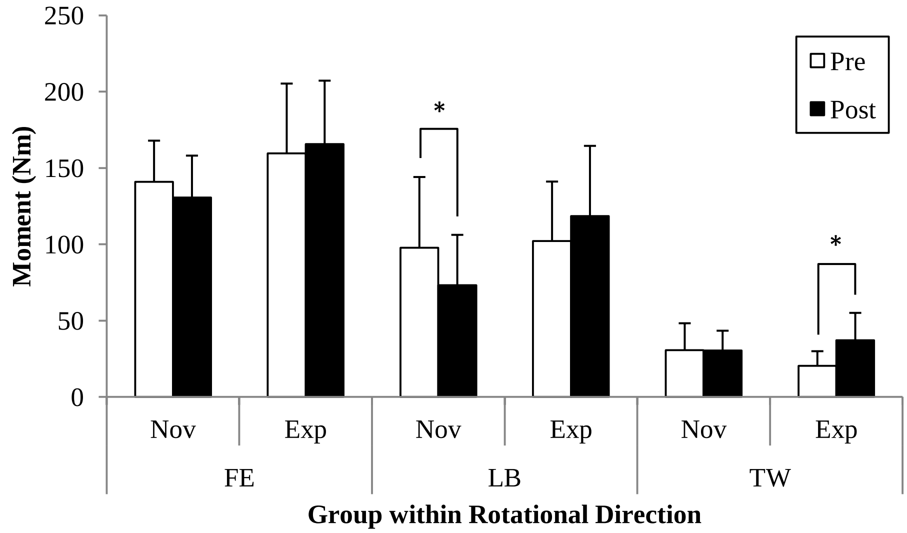

Figure 4.4. Mean values of peak lumbar moments (FE = flexion/extension; LB = lateral bending; TW = twisting) within group (Nov = novice; Exp = experienced). The symbol * indicates significant differences between pre- and post-fatigue conditions, and error bars indicate SDs.

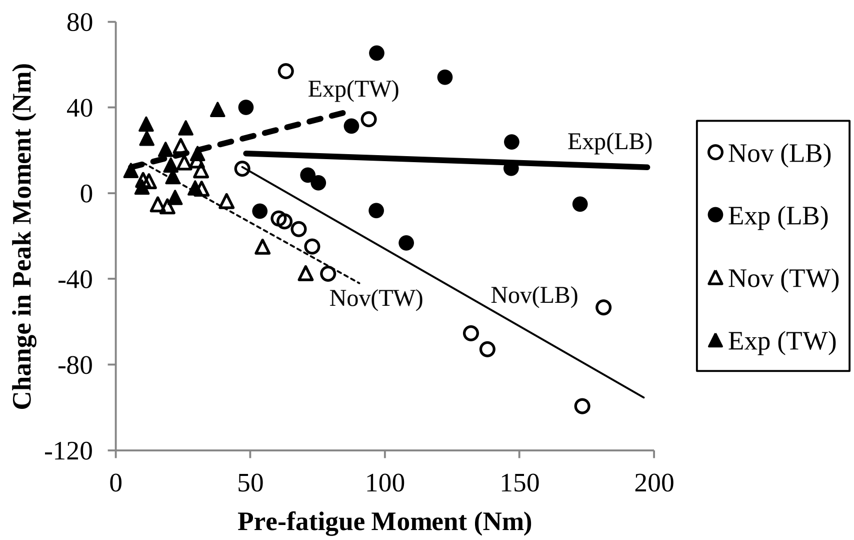

Figure 4.5. Group differences (Nov = novice; Exp = experienced) in the association between pre-fatigue peak torso moments and fatigue-induced changes in these moments, for both the lateral bending (LB) and twisting (TW) directions.

Cumulative lumbar moments significantly decreased in FE and increased in LB and TW, by approximately -9, 29, and 31%, respectively. In the LB and TW directions, novices had consistent cumulative moments, whereas experienced workers exhibited significantly higher cumulative moment post-fatigue (Figure 4.6).

4.3.3. Balance and Stability

Peak linear momenta increased post-fatigue in both the anterior/posterior (AP) and medial/lateral (ML) directions, by roughly 15 and 19%, respectively. Fatigue-induced changes were significantly and negatively associated with pre-fatigue values in the AP and superior/inferior (SI) directions. Although peak angular momenta were not significantly affected by fatigue overall, post-fatigue changes in FE and LB momenta were negatively associated with pre-fatigue values.

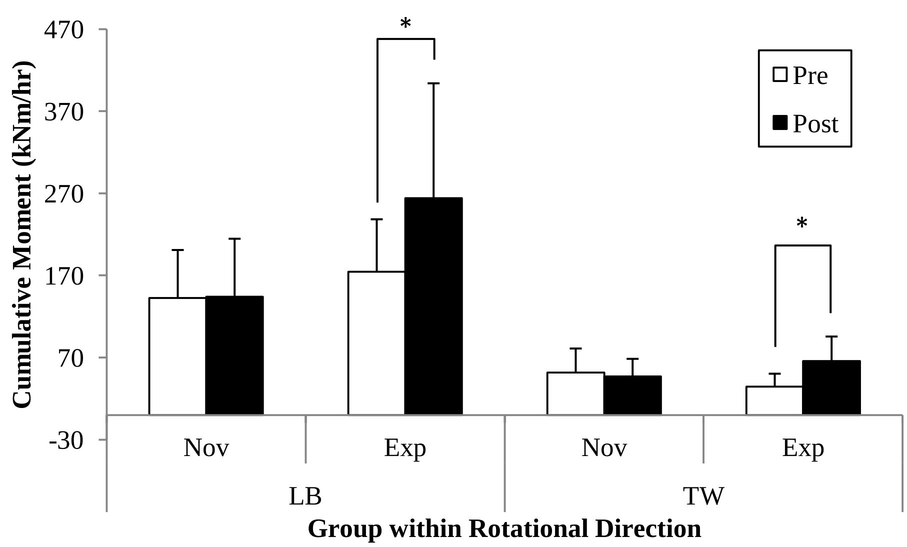

Figure 4.6. Mean values of cumulative lumbar moments (LB = lateral bending; TW = twisting) within group (Nov = novice; Exp = experienced). The symbol * indicates significant differences between pre- and post-fatigue conditions.

FE angular momenta increased (~14%) post-fatigue during lifts, yet were relatively unchanged during lowers. Fatigue-induced changes in LLEs were not significant, though changes in LB values were significantly and negatively associated with pre-fatigue values.

4.3.4. Timing of peak values

There were some significant fatigue-induced changes in the timing of peak values during lifts and lowers (Table 4.3). Overall, peak timing occurred earlier with fatigue, and most significant or substantial changes were associated with movement in the TW direction during lifts, including angular velocities (~13% earlier in the lift duration), angular accelerations (~12% earlier), moments (~26% earlier), and angular momentum (12% earlier). Significant changes in peak timing post-fatigue during lowers were qualitatively similar with those during lifting: LB angular velocities (11% later) and TW moment (27% later). Experience also significantly influenced fatigue-induced changes in peak timing. During lifts, peak LB lumbar angles and angular velocities occurred significantly earlier post-fatigue among novices vs. later post-fatigue among experienced workers. For peak FE lumbar moments, the opposite patterns following fatigue were evident for both groups. Significant effects of experience on fatigue-induced changes in the timing of peak LB angular velocities during lowers were qualitatively similar to those during lifts. From the observed changes in timing across the dependent measures in each group (Table 4.3), it appeared that novices more substantially changed the temporal aspects of their work methods with fatigue (i.e., based on the magnitudes of changes and statistical significance).

Table 4.3. Timing of peak values (% of lift or lower duration). Values shown in bold are significantly (p<0.05) difference between pre- and post-fatigue, while those in italics approached significance (0.05≤p≤0.07). Values in shaded cells indicate significant (p<0.05) effects of experience on fatigue-induced changes (i.e., experience × fatigue interaction effects).

		Lift						Lower					
		Overall		Novice		Experienced		Overall		Novice		Experienced	
		Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Peak lumbar angle	FE	11.1	10.3	8.4	8.2	13.8	12.5	87.8	83.2	95.2	83.6	80.4	82.8
	LB	72.7	68.4	90.8	66.3	54.6	70.6	29.8	30.3	17.2	24.5	42.4	36.0
	TW	82.1	82.9	*92.2*	*83.6*	72.0	82.3	12.2	19.9	15.4	20.0	8.9	19.9
Peak lumbar angular velocity	FE	48.8	47.3	48.0	46.9	49.5	47.7	51.4	49.8	53.4	52.8	49.5	46.8
	LB	67.4	59.4	**76.7**	**57.2**	58.2	61.5	*27.6*	*38.5*	**14.5**	**45.0**	40.7	34.1
	TW	**70.8**	**57.9**	68.7	58.6	72.9	57.2	35.4	41.4	**32.4**	**43.4**	38.4	39.4
Peak lumbar angular acceleration	FE	46.6	51.2	54.7	56.5	38.5	45.8	58.9	56.2	64.5	65.3	53.3	47.2
	LB	47.9	54.4	50.6	50.4	45.1	58.4	38.7	40.9	33.7	38.2	43.6	43.7
	TW	**66.9**	**55.2**	**66.7**	**54.5**	**67.1**	**55.9**	39.8	42.7	36.3	41.4	43.2	44.0
Peak lumbar moment	FE	20.7	24.1	**13.1**	**31.1**	28.2	17.2	76.4	78.1	82.4	78.5	70.4	77.6
	LB	74.1	70.6	76.2	77.4	71.9	63.7	28.1	36.4	**29.2**	**40.6**	26.9	32.2
	TW	**47.4**	**21.1**	**54.4**	**19.2**	**40.5**	**22.9**	**47.6**	**74.5**	**50.9**	**81.3**	*44.4*	*67.6*
Peak linear momentum	AP	30.8	32.1	18.6	18.8	43.1	45.4	52.7	33.2	58.3	52.3	47.0	45.9
	ML	69.1	71.4	**71.1**	**79.0**	67.1	63.9	32.8	33.2	34.9	32.5	30.8	33.8
	SI	33.2	34.1	34.0	35.3	32.4	32.8	58.7	58.5	61.2	59.1	56.3	57.9
Peak angular momentum	FE	36.8	35.6	35.9	37.0	37.7	34.3	59.6	57.2	65.5	57.4	53.6	57.1
	LB	75.5	75.8	78.6	81.7	72.4	69.9	30.5	31.0	30.1	30.5	30.9	31.6
	TW	**63.4**	**51.6**	63.4	49.4	63.4	53.8	34.0	40.1	*35.1*	*44.7*	32.8	35.5

FE = flexion/extension, LB = lateral bending, TW = twisting, AP = anterior/posterior, ML = medial/lateral, SI = superior/inferior

4.4. Discussion

Overall, several fatigue-induced changes in lifting behaviors were evident. For peak torso kinematics, fatigue generally led to higher FE/LB and lower TW values, while for peak torso kinetics fatigue caused lower FE and higher LB/TW values. Particularly for post-fatigue FE kinematics and kinetics, such changes are generally consistent with earlier evidence (Dolan and Adams 1998). Horizontal linear momenta increased post-fatigue, indicating a reduced balance maintenance capability during repetitive lifts/lowers, which is also consistent with an earlier finding (Sparto *et al.* 1997). No significant changes in post-fatigue stability were evident, though the pattern of results, with generally increased post-fatigue LLEs, suggests an elevated sensitivity to small perturbations (i.e., less stable). This pattern is similar to what was reported by Granata and Gottipati (2008), though the magnitude of the effect differed. A possible reason for this discrepancy is differences in the experimental task configurations or characteristics of the participant groups. Shifts from leg- to back-lift techniques, which were observed in an earlier study (Dolan and Adams 1998), were not found here. Specifically, additional analyses yielded no significant or substantial differences between pre- and post-fatigue peak FE angles at the knees (26.8(16.4)° vs. 27.2(8.1)°, respectively) or hips (50.2(17.7)° vs. 51.8(10.7)°, respectively). From these results, the effects of fatigue on WRLBD risks are somewhat unclear, due to opposing patterns of changes in outcome measures (i.e., increased torso kinematics vs. decreased torso kinetics), though fatigue seems to adversely affect balance. Thus, and generally supporting the first hypothesis, fatigue did appear to induce changes in movement strategies during repetitive lifts/lowers.

All significant associations between pre-fatigue measures and fatigue-induced changes in these measures were negative, which may indicate fatigue-induced reductions in between-subject variability. In support of this, additional analyses of variance components were conducted using a fully nested model as in Fethke et al. (2012) and our previous work (Chapter 2). From these analyses, it was found that between-subject variability was reduced post-fatigue for most of the measures exhibiting a significant association. Specifically, between subject variances pre- vs. post-fatigue were 119° vs. 82° for FE angles, 6.8° vs. 2.5° for LB angles, 17.3° vs. 15.5° for TW angles, 190°/s vs. 169 °/s for FE angular velocities, 2340°/s^2 vs. 2330 °/s^2 for FE angular accelerations, 1750 Nm vs. 2000 Nm for peak LB moments, 8.2 kgm/s vs. 6.7 kgm/s for AP linear momenta, 35 kgm/s vs. 10 kgm/s for SI momenta, and 3.8 kgm^2/s vs. 1.0 kgm^2/s for FE angular momenta. Decreased between-subject variability may reflect less flexible movement strategies between workers with fatigue.

Group-level differences in the effects of fatigue were also evident for torso kinetic measures. Specifically, the novice and experienced groups exhibited different patterns of post-fatigue changes in most peak and cumulative torso moments. Novices typically reduced or maintained peak or cumulative moments post-fatigue, whereas experienced workers generally had increased post-fatigue moments. Observed group differences in peak timing may have contributed to these peak moment differences, due to changes in torso postures, torso dynamics, box positions, and box dynamics. Additional analyses related to this timing differences were not conducted, though, due to technical challenges associated with asymmetric lifts/lower (i.e., torso rotations). The opposing patterns of fatigue-induced changes in peak and cumulative moments between groups suggest that novices more focused on reducing torso moments with fatigue than were experienced workers, as we have argued earlier based on measures obtained prior to fatigue (Chapter 2). These fatigue-induced changes suggest that novices may adopt work methods post-fatigue that involved lower risks for WRLBDs, as based on the generally reduced torso kinetics with fatigue seen in this group. One potential confounding factor here is a potential group-level difference in origin/destination heights, though these heights were normalized to individual stature. Additional analyses indicated that vertical locations, here quantified from the ground to the top of the box, likely did not contribute substantially to group-level differences in torso kinetics: vertical distances at the origin/destination were 0.63(0.15) vs. 0.63(0.18) m and 1.25(0.06) vs. 1.16(0.10)m for novices vs. experienced workers, respectively.

Other than peak and cumulative lumbar moments, fatigue-induced changes were not significantly different between groups. Of note, pre-fatigue group differences in torso kinematics, balance, and stability were not formally analyzed here, as these differences were presented in earlier work (Chapters 2 and 3). However, most group differences that were found significant in previous work (Chapters 2 and 3) were diminished here post-fatigue, except for torso kinetics. Thus, fatigue may reduce group differences in the remaining measures (i.e., torso kinematics, balance, and torso movement stability).

Group differences in post-fatigue adaptations were also found in terms of triaxial behaviors/coordination, though some of these were not significantly different between groups. Specifically, novices generally had reduced post-fatigue kinematics, kinetics, angular momenta, and LLEs in the TW direction. In contrast, experienced workers generally had increased post-fatigue kinematics, kinetics, and LLEs in the LB direction, and relatively consistent post-fatigue TW kinematics. As such, novices may have tried to avoid torso twisting with fatigue, while experienced workers used more lateral bending of the torso. An earlier study (van Dieën *et al.* 1998) also observed more use of torso lateral bending or twisting with fatigue during repetitive, symmetric lifts/lowers, and the authors concluded that such changes may be related to adaptations to reduce further fatigue development. Similarly, the group differences found here in the patterns of switching between triaxial behaviors indicate that each group may different strategies to offload fatigued muscles by recruiting/derecruiting different muscle groups.

To summarize the group-level differences resulting from fatigue, novices generally reduced or maintained torso kinetics post-fatigue while experienced workers typically increased these. Although fatigue-induced changes in the remaining measures were not significantly different between groups, differences in triaxial loading behaviors with fatigue were found between groups. Thus, and generally supporting the second hypothesis, novice and experienced workers responded to fatigue differently.

Potential limitations of this study are similar to those indicated earlier (Chapter 2), including participant recruitment, the small sample size, and use of specific task configurations. Other potential limitations should be noted. First, fatigue levels were not quantified. Task demands across all participants exceeded ~20% of maximum capacity, as estimated from mean lumbar moment during the experimental tasks (~70Nm) relative mean lumbar eccentric strength (~360Nm). Note, the latter was chosen as the larger between eccentric and concentric isokinetic strength, to provide a conservative estimate of minimum percentage of capacity. With the current task configuration and estimated exertion levels, the level of induced fatigue was likely substantial based on findings in previous studies (Jørgensen *et al.* 1985, Petrofsky and Lind 1978, Potvin and Norman 1993, van Dieën *et al.* 1996). Also, our pilot work (with 12 participants), using the Borg CR-10 scale (Borg and Borg 2001) to rate discomfort, indicated a “strong” level of discomfort overall (mean(SD) = 5.0(1.9)) and at the low back (5.29(2.43)). However, fatigue levels may not have been consistent between participants, since actual and/or perceived fatigue levels can depend on individual differences such as personal fitness, muscle endurance, and work experience (Cloutier 1994, Mital 1987, Parakkat *et al.* 2007).

In summary, fatigue during a repetitive, asymmetric, lifting/lowering task decreased balance maintenance capability, and which may imply a higher risk for falls. Effects of fatigue on WRLBD risks, were less clear, though, since changes in torso kinetics and kinematics were in opposing directions. While several pre-fatigue differences between the experienced and novice groups were observed, specifically regarding the use of torso lateral bending and twisting, fatigue seemed to largely negate many of these group-level differences, specifically peak torso kinematics, balance, and torso movement stability, but not torso kinetics. With fatigue, novices may adapt their work methods in ways that reduce WRLBD risks, though this was not found among experienced workers. Thus, and similar to conclusions in previous work (Chapter 2), observed work methods among experienced workers may not be an appropriate model for training programs that intend to reduce WRLBD or fall risks. However, the current findings may be applicable for only certain task configurations. Further investigation is needed to understand the underlying mechanisms responsible for fatigue-related adaptations in work methods, and to determine whether training programs should incorporate the movement strategies of experienced workers as a model.

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Chapter 5: Effects of work experience on work methods and work-related low back disorder risk during dynamic pushing and pulling

Abstract

Pushing and pulling are potential risk factors for work-related low back disorders (WRLBDs). While several studies have evaluated differences in work methods related to experience, evidence related to dynamic pushes/pulls is limited. Eight novices and eight experienced workers completed dynamic tasks in several configurations (pushing vs. pulling and preferred vs. elbow handle heights), using a cart weighted to 250% of individual body mass. Hand forces, torso kinematics/kinetics, torso kinetics, and slip risks were assessed. Observed differences in work methods between groups suggested less efficient use of hand forces and more use of torso accelerations to achieve cart motion among novices. Experienced workers used work methods involving lower torso kinematics/kinetics, suggestive of a lower risk for WRLBDs, though these effects of experience were often relatively small and were inconsistent across the task configurations investigated. Thus, strong conclusions regarding the effects of experience on WRLBD risks during dynamic pushing/pulling tasks were not warranted. Additional studies are needed to characterize the effects of work experience, and to support the use of the work methods of experience workers as a model for risk reduction (i.e., using training programs).

Keywords: experience; low back; pushing; pulling; RCOF; biomechanics

5.1. Introduction

Work-related low back disorders (WRLBDs) continue to be important occupational problems, accounting for ~13% of all nonfatal occupational injuries requiring days way from work in the U.S. in 2010 (BLS 2011a). Associated costs are also substantial, with WRLBDs responsible for the highest portion (~20%) of all occupational injury costs in the U.S. (Leigh *et al.* 2006b). Manual material handling (MMH) in particular has been noted as an important source of such occupational injuries (Kuiper *et al.* 1999). MMH tasks include lifting, lowering, pushing, pulling, and carrying. Of these, pushing and pulling has received relatively less attention (i.e., vs. lifting/lower), in relation to WRLBDs. Indeed, it is difficult to conclude that a clear causal pathway exists between pushing/pulling and WRLBDs, particularly given the relatively moderate levels of exposures involved as assessed by biomechanical measures (Roffey *et al.* 2010). Biomechanical exposures are probably main contributors to injury risk (Marras 2000), though the specific pathways leading to WRLBDs are likely complex. Epidemiological evidence does indicate a potential association between pushing/pulling and WRLBDs (Hoozemans *et al.* 1998), and musculoskeletal control has been noted as an important focus of study with respect to the risk of a low back injury (Preuss and Fung 2005).

Of particular interest in the current study is work experience, and which is often considered to lead to motor control strategies or work methods that are pre-programmed. However, the specific purposes of the strategies/methods used by experienced workers are currently unclear, particularly in terms of WRLBDs. Furthermore, mixed results have been reported regarding the specific differences in work methods related to experience (for review, see Chapter 2), especially during lifting/lowering tasks. In brief, some studies have reported lifting techniques among experienced workers that appear protective (Authier *et al.* 1996, Gagnon 1997, Keir and MacDonell 2004, Marras *et al.* 2006), whereas others demonstrated that such benefits may be inconsistent or task specific (Granata *et al.* 1999, Lee and Nussbaum 2012, Plamondon *et al.* 2010). Effects of experience have been reported for a variety of other occupational tasks (Gregory *et al.* 2006, Gregory *et al.* 2009b, Madeleine *et al.* 2003, Madeleine *et al.* 2008, Pal *et al.* 2010). Some of these studies also showed that work experience does not contribute consistently to reduced WRLBD risk (Gregory *et al.* 2006, Gregory *et al.* 2009b). Thus, the association between work experience and WRLBDs is likely to differ substantially between specific tasks or contexts.

Evidence regarding the effects of experience for dynamic pushing/pulling is limited. Chang et al. (2000) reported that experience acquired during five-days of practice in static pulling let reduced lumbar moments, and Lett and McGill (2006) found that experienced firefighters used lower hand forces and lumbar torques during static pushing/pulling. However, static vs. dynamic pushing/pulling may result in different biomechanical demands and measures. For example, differences in peak or maximum acceptable hand forces between pushing and pulling depend on whether the tasks are static or dynamic (Hoozemans *et al.* 1998). To the author's knowledge, no existing study has assessed the effects of experience on torso kinematic/kinetic measures related to WRLBD risks, during dynamic pushes/pulls. Although a recent study reported the effects of experience on hand forces during dynamic pushing (Boyer *et al.* 2013), more direct relationships between experience and WRLBDs were not examined. The current study sought to determine whether and how work experience affects work methods used during dynamic pushing/pulling, as assessed by multiple biomechanical measures. We hypothesized that experienced workers would exhibit distinct work methods during dynamic pushing/pulling, as has been reported for static tasks (Lett and McGill 2006). Identifying such differences may help guide future approaches to reduce WRLBD risk, such as training for novice workers as has been suggested earlier (Gagnon 2003, Lett and McGill 2006).

5.2. Methods

5.2.1. Participants

Eight novices and eight experienced workers completed the study, with six males and two females in each group (Table 5.1). This sample size was selected, based on a *priori* power analysis, to provide adequate statistical power (≥0.8) to detect group differences in peak torso kinetics using peak spinal compression forces reported in an earlier, related study (Lett and McGill 2006). All participants reported no current or prior musculoskeletal disorders and completed informed consent procedures approved by the Virginia Tech Institutional Review Board (Appendices A and B). Experienced workers were recruited from among workers working currently in jobs requiring "frequent push/pull tasks", which were operationally defined as involving pushing/pulling conducted 10 hrs/week on average. All experienced workers reported a minimum of 1.5 years of recent experience in such tasks.

Table 5.1. Participant information (means (SD)) and results of *t*-tests comparing the Novice and Experienced groups.

	Age (yrs)	Experience (yrs)	Stature (m)	Body Mass (kg)	Lumbar Isokinetic Strength (Nm)	
					Flexion	Extension
Novice	20.6 (1.1)	0.0 (0.0)	1.77 (0.08)	81.2 (12.1)	238.3 (92.5)	317.3 (65.0)
Experienced	20.9 (1.4)	2.7 (1.0)	1.78 (0.09)	79.8 (10.1)	231.3 (42.2)	312.3 (39.1)
Test result	t = -0.41 p = 0.69	- -	t = -0.33 p = 0.75	t = 0.26 p = 0.80	t = 0.14 p = 0.89	t = 0.26 p = 0.80

Novices were local student volunteers who reported no experience in frequent push/pull tasks, and they were selected to achieve age matching (± two years), at the individual level, with experienced workers.

5.2.2. Experimental protocols

Initially, isokinetic, concentric lumbar flexor/extensor strength was measured for each participant to evaluate potential group differences in strength relevant to the experimental task. Maximum voluntary contractions (MVCs) were performed with a commercial dynamometer (Biodex System 3 pro, Biodex Medical Systems Inc., NY, USA), and using a custom fixture that isolated (immobilized) the pelvis and lower extremities. Strength testing included initial warm-up and rest, and data collection during a minimum of five MVCs, interspersed with two-minute rest breaks to minimize potential fatigue. Concentric efforts were done at 120°/s, with a range of motion from 0° (upright) - 80° (torso flexion). These parameters were selected to obtain high reliability (Keller *et al.* 2001). Gravitational effects on body segments and the dynamometer were accounted for.

Additional rest (a minimum of ~30 min) was provided after strength testing was completed.

A cart (width = 76cm and length = 124cm including handles) was used for push/pull trials, which had two swiveling hard plastic (nearest to handles) and two non-swiveling pneumatic wheels, and which was modified to allow for height-adjustable handles (Figure 5.1). Pressure in each pneumatic wheel was controlled at ~70 kPa, and the cart mass was set to 250% of individual body mass . This cart mass was selected, in pilot work, to yield peak and mean hand force comparable with an earlier study (Lett and McGill 2006), and to not exceed maximum acceptable force limits (50%ile) for ~2m pushes (Snook and Ciriello 1991). Before data collection, several practice trials were completed, during which each participant self-selected a "preferred" handle height.

Participants completed trials in four task configurations, involving pushing and pulling at handles set at preferred and elbow heights. The order of configurations was counterbalanced using Latin-squares. Following additional practice trials (10 pushes or pulls), participants completed three replications of a push or pull at the set handle height. Prior to each trial, the cart's wheels were aligned parallel to the direction of motion. Throughout, free-style work methods and preferred work speeds were used, and no specific instructions were provided regarding work methods. All participants began the trials with each foot completely on one of the force platforms, with a self-selected spacing.

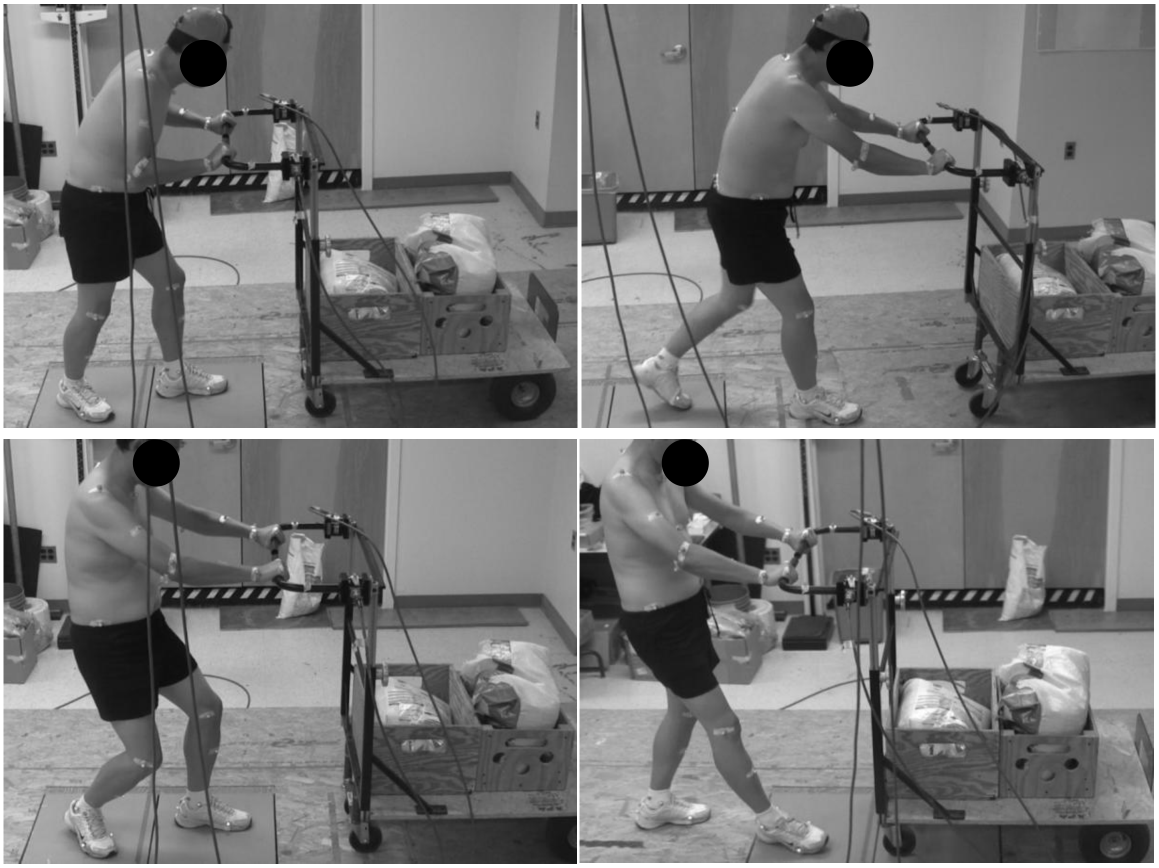

Figure 5.1. Task configuration using a height adjustable hand-held cart during pushing (upper) and pulling (lower) from task initiation (left) to termination (right).

Each participant moved the cart ~2m (~ three steps) in each trial, and actively stopped the cart at the end. All participants wore shoes that had soles composed of relatively consistent materials (rubber), as are common for commercial athletic shoes.

5.2.3. Data collection and processing

Reflective markers were attached over anatomical landmarks as in Dumas et al. (2007) and to the cart, and tracked at 60 Hz with a 7-camera system (Vicon Motion System Inc., CA, USA). To improve accuracy in reconstructing joint centers and segmental kinematics, additional markers were attached over relatively immobile body parts:

vertebral process of T10 (torso), mid-way between the bilateral posterior superior iliac spines (pelvis), the anterior borders of the tibias (shank), lateral aspect mid-way between head vertex and occiput (head), mid-way between the acromion and lateral humeral epicondyle (upper arm), and approximately mid-way between the ulnar styloid and lateral humeral epicondyle (lower arm). Bilateral ground reaction forces (GRFs) and hand forces were sampled at 960 Hz, respectively using two force platforms (OR6-7-1000, AMTI, MA, USA) and two 3-axis load cells (MC3A-6-250 & -500, AMTI, MA, USA). Marker and force data were low-pass-filtered (zero-lag, 2nd-order Butterworth), with respective cut-off frequencies of 5 and 10 Hz, and force data were then down-sampled to 60 Hz.

Windows of data were extracted, from task initiation to the time at which the second foot left the ground ("foot-off", see Figure 5.1). Task initiation time, for both pushing and pulling, was determined when absolute values of horizontal cart velocity exceeded 0.1 m/s for $\geq$ 0.5 s, similar to the method in Hoozemans et al. (2004), and these velocities were derived using five-point derivatives of marker positions on the cart (Kingma *et al.* 1998). Foot-off time was determined using the vertical component of GRFs, specifically by determining when these went below 10 N; this approach is similar to earlier methods used to identify heel contacts during gait (Cham and Redfern 2002, Kim *et al.* 2005). Of note, specific forces due to foot contact cannot be obtained if this contact occurs while the cart crossed a force platform. This potential difficulty was examined, but no simultaneous contacts were found (all vertical GRFs dropped < 10N before the cart moved to the force platform). Across all trials, mean (SD) task duration (from task initiation to second foot-off) was 1.65(0.37) s.

5.2.4. Dependent measures

Multiple measures were obtained to characterize WRLBD and slip risk, and included hand forces, torso kinematics, torso kinetics, and required coefficient of friction (RCOF). Hand forces during the push/pull trials were characterized using the peak and mean hand forces along three orthogonal axes (anterior/posterior = AP, medial/lateral = ML, and superior/inferior = SI). Forces were summed across the two hands, and the total triaxial forces were transformed to a global coordinate system (GCS) from a cart-centered local coordinate system (LCS); note, only small deviations between the two coordinate systems were found.

For calculations of torso kinematics and kinetics, similar procedures were used as in Chapter 2, and brief descriptions are provided here. To assess torso kinematics and kinetics, a 3D linked-segment model with 15 body segments was developed, with segmental masses, inertial tensors, and center-of-mass (COM) locations based on scaling methods in Dumas et al. (2007). Torso kinematics were summarized using peak triaxial torso angles, angular velocities, and angular accelerations (Winter 2004a). For these kinematics, Euler angles were used (X = flexion/extension, Y = lateral bending, and Z = twisting), and with an XYZ rotation sequence. Torso kinetics were summarized using peak and cumulative triaxial L5S1 moments, using a “top-down” approach similar to that described in Lee et al. (2011), and were then converted to original units after normalizing to individual body mass and stature (Chapter 2). Peak torso kinematics and kinetics were not available for one trial by an experienced worker (a pull trial with elbow handle height), due to incomplete detection of markers. Cumulative moments were calculated as the sum of absolute values of instantaneous moments from task initiation and termination (second foot-off), and reported per hour duration. Torso kinematics and kinetics are presented below with respect to a GCS and LCS (relative to the pelvis), respectively, and about functional axes: flexion/extension (FE), lateral bending (LB), and twisting (TW).

Slip risk was quantified using RCOF, with respect to a GCS, which was derived from the instantaneous ratio of horizontal (resultant forces in the X and Y directions) to vertical GRFs (Burnfield and Powers 2006). Additional criteria were applied to avoid spurious RCOF values. Specifically, instantaneous RCOFs were excluded if: 1) vertical GRFs were < 50N, suggesting a non-critical situation (Burnfield and Powers 2006); 2) horizontal GRFs were < 50N; or 3) foot velocities exceeded 0.2m/s (toe and heel velocities were used during pushes and pulls, respectively). The latter two criteria were added for several reasons. During pushing or pulling of heavy carts, horizontal forces are substantially higher than during walking. For example, peak AP GRFs during walking are ~20% of body weight (Simpson and Jiang 1999), while peak AP GRFs during pulling are ~300N (Andres and Chaffin 1991). Thus, relatively small magnitudes of horizontal forces may have only a minor influence during actual tasks. Also, the lowest foot speeds when slips occur have been indicated as ~0.23m/s (Redfern *et al.* 2001). In the current study, no slips occurred during any trials, which was determined by analyzing foot velocities and accelerations using a reported data set for heel contact dynamics during slips (Cham and Redfern 2002). Thus, the velocity limit of the latter criteria was considered reasonable. All peak values were determined from absolute values of each dependent measure.

5.2.5. Statistical analysis

Separate three-way, mixed-factor analyses of variance (ANOVAs) were used to assess the effects of experience (E), push/pull (P), and handle height (H) on hand forces, torso kinematics and kinetics, and slip risk. To explore significant interaction effects, post-hoc pairwise comparisons were done using Tukey's Honestly Significant Difference (HSD). Potential group differences in cart travel distances, mean and peak cart velocities, and handle heights, which may have acted to confound the effects of experience, were evaluated using unpaired *t*-tests. Statistical analyses were done using JMP™ (v9, SAS Institute Inc., NC, USA), with significance concluded when $p < 0.05$, and summary results are presented as means (SDs). The presentations of results focuses only on main and interactive effects related to experience.

5.3. Results

No significant or substantial differences were evident between the experienced and novice groups, in terms of age, anthropometry, or lumbar flexor/extensor strength (Table 5.1). Other potential confounding effects (i.e., group-level differences) were similarly not significant or substantial (Table 5.2). Regarding the dependent measures, one significant main effect of experience and several interactive effects were found (Table 5.3), details regarding which are provided below, separately for each set of measures.

Table 5.2. Mean (SD) of cart kinematics and handle heights, and results of *t*-tests comparing the Novice and Experienced groups.

	Cart kinematics			Handle height	
	Mean distance (m)	Mean velocity (m/s)	Peak velocity (m/s)	Preferred (m)	Elbow (m)
Novice	0.74(0.17)	0.44(0.07)	0.66(0.10)	1.04(0.07)	1.13(0.06)
Experienced	0.72(0.16)	0.45(0.08)	0.69(0.12)	1.04(0.08)	1.14(0.07)
Test result	t = 0.24 p = 0.81	t = -0.27 p = 0.79	t = -0.54 p = 0.60	t = 0.00 p = 1.00	t = -0.31 p = 0.76

Table 5.3. ANOVA results for main and interactive effects of experience (E), push/pull (P), and handle height (H). Values shown in bold are significant (p < 0.05), while those in italics approached significance (0.05 ≤ p ≤ 0.07). Entries for the Novice (Nov) and Experienced (Exp) groups are means (SD).

			Nov	Exp	E	E×P	E×H	E×P×H
Hand force	Peak force (N)	AP	297(61)	318(108)	0.60	**0.0001**	0.85	0.74
		ML	38.5(13.3)	43.1(14.8)	0.22	0.71	0.15	0.91
		SI	91.3(34.7)	88.2(31.7)	0.77	0.80	*0.056*	0.74
	Mean force (N)	AP	153(29)	160(49)	0.72	**0.0016**	0.95	0.31
		ML	11.3(7.6)	14.6(7.8)	**0.034**	**0.0058**	0.97	0.73
		SI	35.9(27.5)	29.9(26.5)	0.25	0.79	0.81	0.31
Torso kinematics	Peak angle (deg)	FE	24.8(11.8)	20.2(10.6)	0.23	0.23	0.16	0.45
		LB	4.1(2.4)	3.3(1.6)	0.36	0.62	0.62	0.15
		TW	0.1(4.0)	2.0(2.6)	0.10	**0.0041**	**0.046**	0.63
	Peak ang. vel. (deg/s)	FE	25.3(10.8)	20.1(9.3)	0.18	0.51	0.29	0.73
		LB	11.1(5.7)	7.2(2.9)	**0.040**	0.70	0.82	**0.0092**
		TW	12.4(6.6)	11.8(4.6)	0.98	0.33	0.68	0.48
	Peak ang. acc. (deg/s^2)	FE	98.5(40.7)	84.2(53.3)	0.25	0.53	0.34	0.20
		LB	51.1(24.9)	36.2(14.1)	0.10	0.89	0.98	0.10
		TW	61.6(33.9)	55.0(26.6)	0.42	0.53	**0.033**	0.77
Torso kinetics	Peak moment (Nm)	FE	49.2(40.7)	40.5(25.9)	0.67	0.45	0.39	0.55
		LB	21.8(11.8)	20.5(11.1)	0.80	**0.016**	0.10	0.50
		TW	17.5(9.6)	16.3(7.5)	0.95	**0.0042**	0.91	0.85
	Cum. moment (kNm/hr)	FE	6596(7296)	4816(3611)	0.60	0.24	0.23	0.62
		LB	2564(1773)	2408(1649)	0.79	**0.0017**	0.77	0.69
		TW	1971(1267)	1804(987)	0.73	**0.0075**	0.95	0.10
Slip risk	Peak RCOF		0.39(0.04)	0.39(0.05)	0.88	**0.042**	0.17	0.12

FE = flexion/extension, LB = lateral bending, TW = twisting, AP = anterior/posterior, ML = medial/lateral, SI = superior/inferior, Nov = novice, Exp = experienced

5.3.1. Hand force

For peak hand forces, no significant main effects of experience were found (Table 5.3), though several interactive effects associated with experience were significant or approached significance (Figure 5.2). Regarding the E×P interaction, both groups pushed the cart with similar peak AP forces, though experienced workers pulled the cart with ~15% higher peak AP forces. In the SI direction, the E×H interaction approached significance; preferred handle heights resulted in higher peak forces (~12%) among novices, whereas elbow heights yielded the opposite pattern. A significant E×P interaction effect was evident for mean AP forces (Figure 5.3), with a pattern that was qualitative similar to that for peak AP forces. Both main and interactive effects of experience were found for mean ML forces (Figure 5.3). Experienced workers generated higher mean ML forces during both pulls and pushes vs. novices, though this difference more substantial during pushes (experienced used ~74% higher vs. novices).

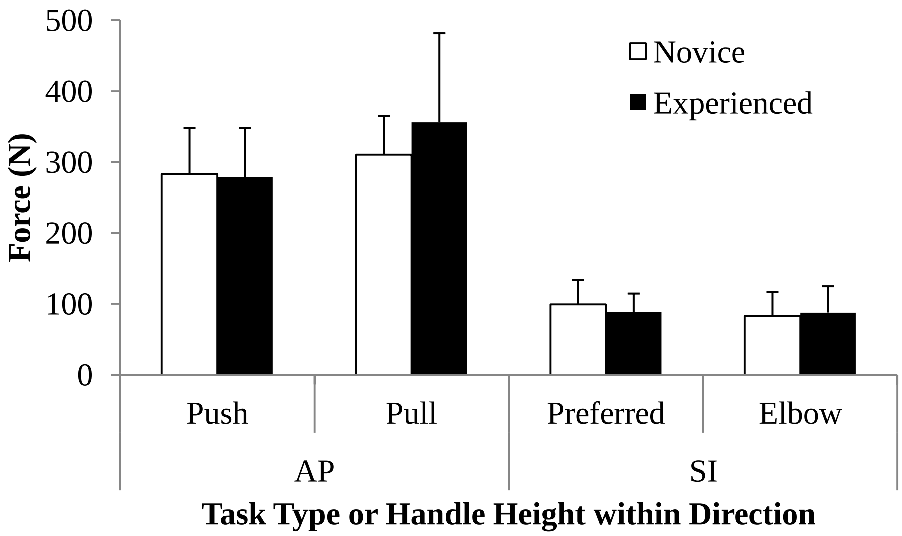

Figure 5.2. Peak hand forces (AP = anterior/posterior, SI = superior/inferior) during different task configurations (push vs. pull, preferred vs. elbow handle height). Error bars indicate SDs.

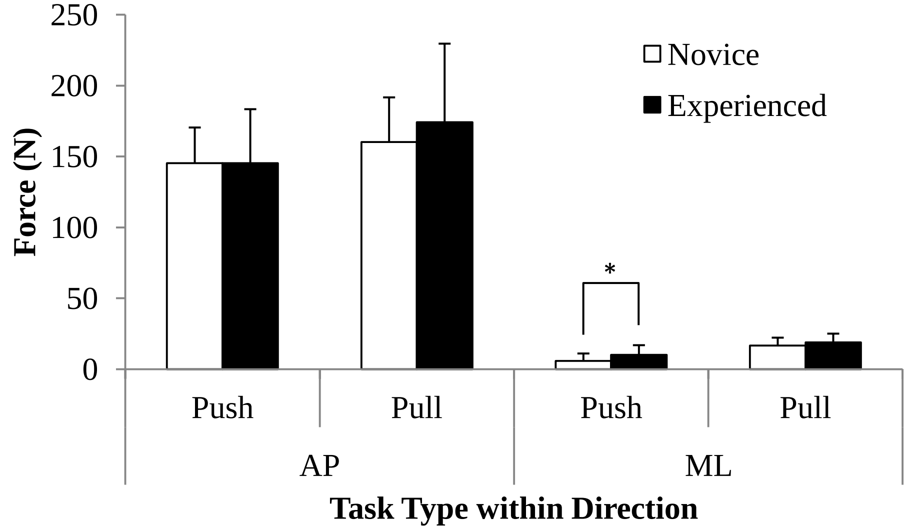

Figure 5.3. Mean hand forces (AP = anterior/posterior, ML = medial/lateral) during different task types (push vs. pull). The symbol * indicates a significant difference between groups. Error bars indicate SDs.

5.3.2. Torso kinematics

While there were no significant main effects of experience on peak torso angles, the E×P and E×H interaction effects on peak TW angles were significant. Group-level differences in peak TW angles were small (~0.1°) during pushes, though experienced workers had substantially (~30%) lower peak angles during pulls (Figure 5.4). Regarding the E×H interaction effect, group-level differences in peak TW angles were relatively small (~0.5 deg) in both handle conditions. Significant main and interactive effects of experience were evident for peak torso LB angular velocities. Novices overall hand higher peak torso LB velocities, though the difference between groups varied between task configurations (Figure 5.5). Although no significant main effects were found for peak torso angular accelerations, there was a significant E×H interaction effect on peak torso TW accelerations. There were relatively small differences (~3°/s^2) in peak SI accelerations with the elbow height handle, while experienced workers used ~25% lower peak SI accelerations with the preferred handle height (Figure 5.6).

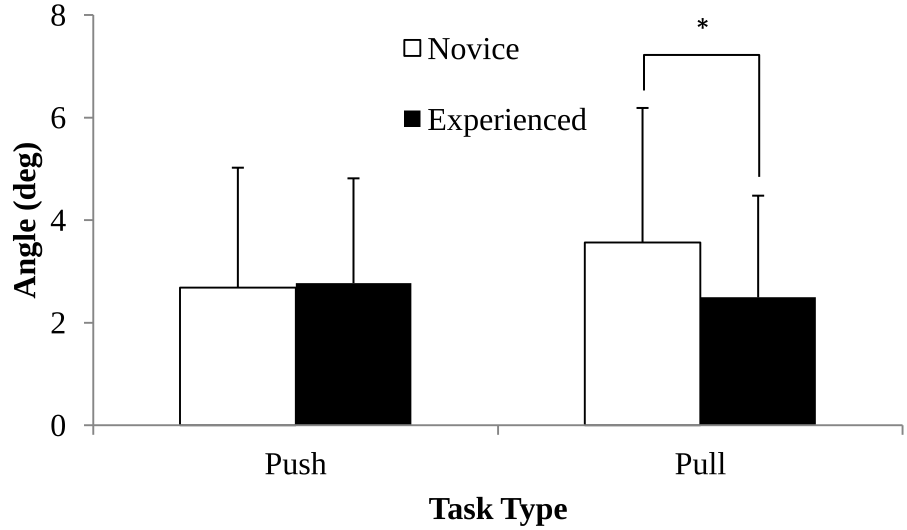

Figure 5.4. Peak torso TW angles during different task types (push vs. pull). Error bars indicate SDs.

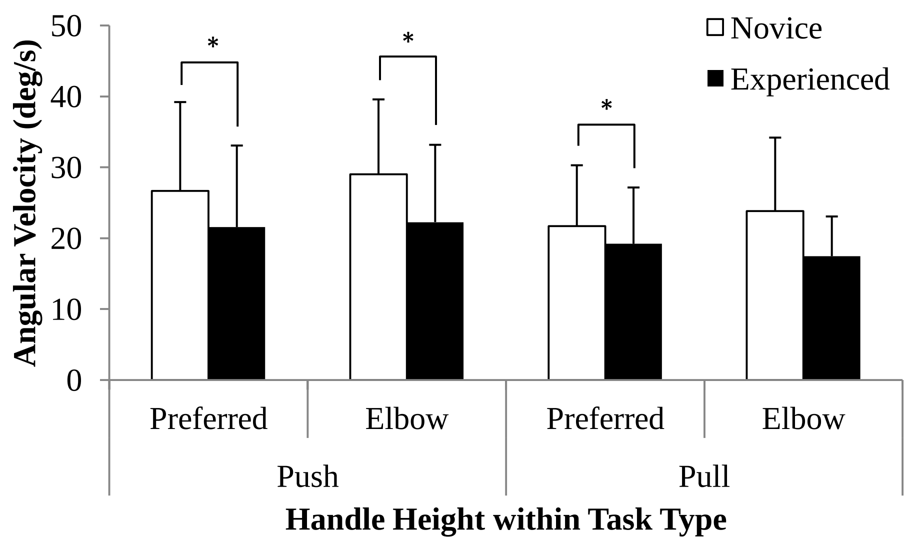

Figure 5.5. Peak torso SI angular velocities during different task types (push vs. pull) with different handle heights (preferred vs. elbow). Error bars indicate SDs.

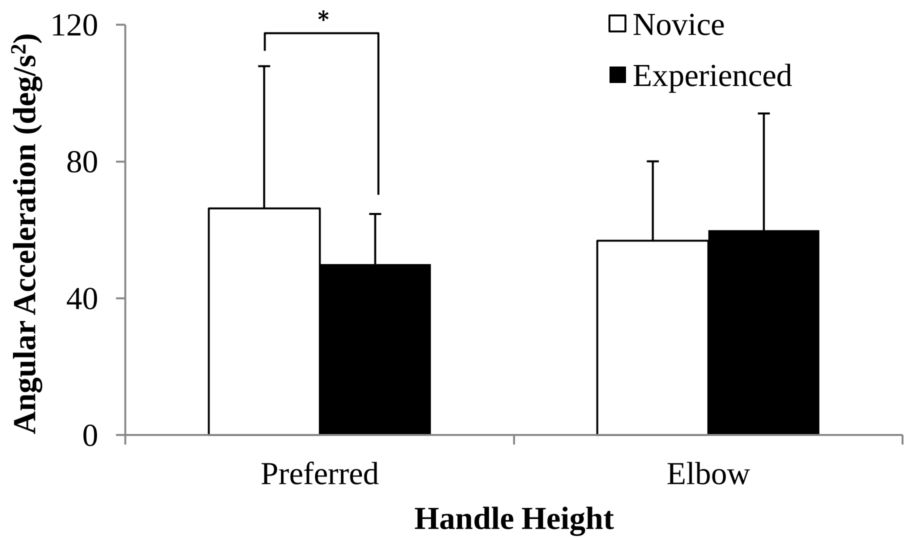

Figure 5.6. Peak torso TW angular accelerations during different handle heights (preferred vs. elbow). Error bars indicate SDs.

5.3.2. Torso kinetics

There were no main effects of experience on either peak or cumulative moments. For the E×P interaction effect on peak torso LB moments, experienced workers exhibited higher values during pushes and lower values during pulls (Figure 5.7). For peak torso TW moments, the patterns of group differences during each task type were opposite compared to peak LB moments. Similar to peak moments, significant E×P interaction effects on cumulative LB and TW moments were found (Figure 5.8). For cumulative torso LB moments, experienced workers had higher values during pushes and lower values during pulls vs. novices. The pattern of group-level differences in cumulative TW moments was opposite to those for peak TW moments.

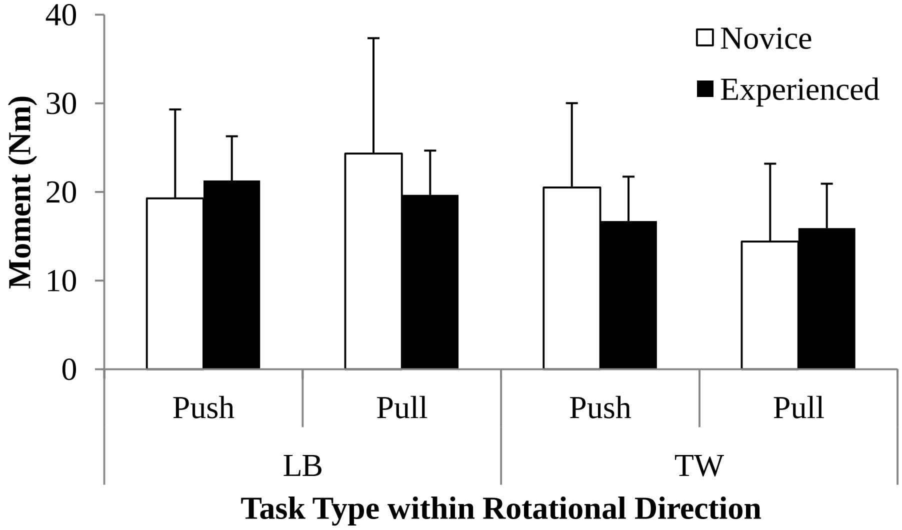

Figure 5.7. Peak lumbar twisting moments during different task type (push vs. pull). Error bars indicate SDs.

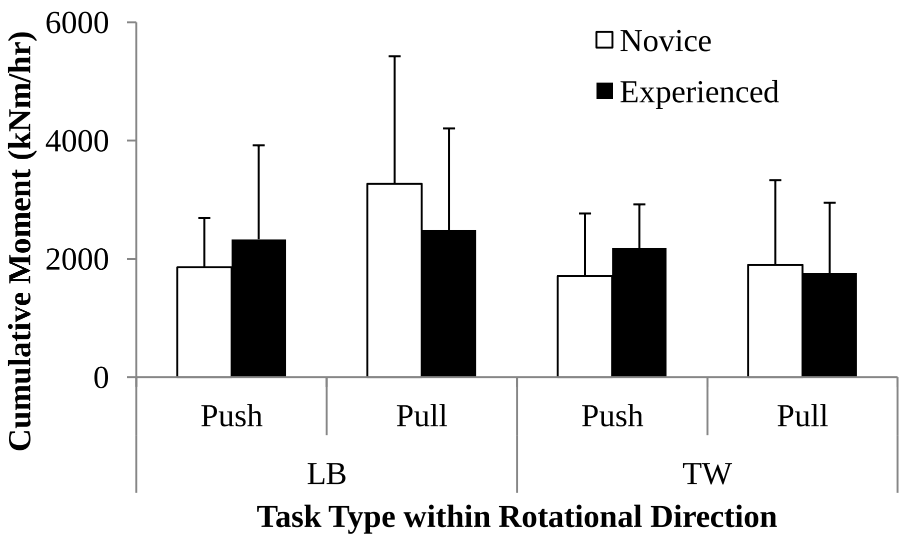

Figure 5.8. Cumulative lumbar moments during different task type (push vs. pull). Error bars indicate SDs.

5.3.3. Slip risk

No main effects of experience on RCOF were found, though there was a significant E×P interaction effect (Figure 5.9). Experienced workers exhibited slightly lower RCOF values during pushes vs. novices, whereas the opposite pattern was found during pulls. Notably, these group-level differences were quite small.

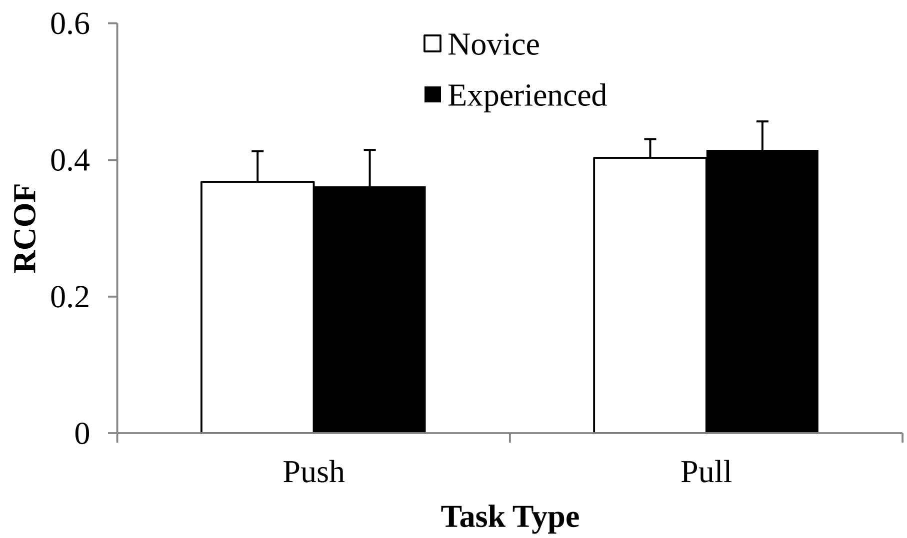

Figure 5.9. Peak values of required coefficient-of-friction (RCOF) during different task type (push vs. pull). Error bars indicate SDs.

5.4. Discussion

Experienced workers overall used higher mean ML hand forces, which indicates the use of hand forces other than to move the cart in purely forward/backward direction. ML forces were more substantial during pushing vs. pulling, consistent with an earlier study (Boyer *et al.* 2013) wherein experienced nurses showed higher lateral deviations of a cart during pushing. Although not significant, however, experienced workers overall also used higher hand forces in the AP direction and lower SI forces (which, like ML forces, do not contribute to primary motion). The group-level differences in AP hand forces here are consistent with an earlier report on dynamic pushing (Boyer *et al.* 2013), and higher AP and lower SI forces are considered as efficient strategies among experienced workers (de Looze *et al.* 2000). As a whole, the current results may indicate that experienced workers sought to more tightly control cart travel along the primary (AP) direction, and used larger ML forces to achieve this. In addition, the direction of peak and mean SI forces were generally downward for both pushes and pulls.

Regarding differences between pushing and pulling, both groups used higher peak and mean hand forces in the AP direction during pulls vs. pushes. Qualitative differences in peak AP hand force between pushes and pulls in the current study are consistent with an earlier report (Al-Eisawi *et al.* 1999) but contrary to another (Boocock *et al.* 2006), both of which examined dynamic pushing vs. pulling. A difference in test conditions (e.g., use of rails on a moving path in Boocock et al. (2006)) may account for the latter discrepancy. Of note, task-related differences in AP forces found here were more substantial among experienced workers. Specific reasons for these group-level differences between pushes and pulls are currently unclear.

Experienced workers had lower peak torso kinematics in all directions (though this group-level difference was only significant as a main effect on peak torso LB angular velocities). Peak torso angular velocities, specifically, were lower among experienced workers in all triaxial directions, and work methods may have been adopted in this group to control linear momenta that are related to balance maintenance (Kaya *et al.* 1998). Additional analyses indicated that experienced workers exhibited slightly (~1-~4 %) higher peak linear momenta (including the cart) normalized to individual stature and body mass as in Chapter 3, in all directions. Thus, for balance maintenance, experienced workers seemed to restrict torso movement to counteract higher linear momenta that may negatively affect balance maintenance capability. Novices adopted higher peak torso accelerations in all triaxial directions, and may thus rely more on torso accelerations or dynamic forces from the torso to move the cart. In contrast, experienced workers may depend less on torso accelerations, and instead use contributions from other sources (e.g., upper or lower extremities).

For torso kinetics, although not significant as main effects, experienced workers overall had lower peak and cumulative torso moments in all triaxial directions. Chang et al. (2000) reported that experience, specifically through a five-day practice period, reduced peak torso moments during static pulling. Lett and McGill (2006) also reported that experienced firefighters exhibited lower peak torso moments during static pushing/pulling. These are consistent with our results for peak FE torso moments (novice = 64.5(50.9)Nm vs. experienced = 51.4(32.0)Nm during pulling). In the LB/TW directions, pulling generally resulted in lower peak/cumulative torso moments among experienced workers, though the opposite pattern of group-level differences (higher peak/cumulative moments among experienced workers) was found during pushing. However, the LB/TW directions may be of less practical importance due to the relatively small differences found between groups. As such, the lower torso FE kinetics observed among experienced workers suggests a lower risk for WRLBDs, though levels of exposures to WRLBD risk appeared low or moderate in both groups.

Several potential limitations in this work should be noted. First, the current sample size was derived from earlier results regarding static tasks, and as a result may have been underpowered for dynamic tasks. Second, only a few specific conditions were examined, including a single (normalized) cart mass, one specific cart, and two handle heights, and involved controlled initial foot positions, self-selected moving speeds, and a relatively short travel distance. Work methods, and group- and task-level differences in these, may be dependent on these aspects of the study design. Future work is clearly needed to assess such dependency, and to determine the influences of work experience more broadly during push/pull tasks.

In summary, and in support of the study hypothesis, experienced workers used different work methods than novices during dynamic pushes and pulls. These group-level differences, though, were typically distinct for pull vs. push efforts. Observed group-level differences were also suggestive of more efficient use of hand forces and more reliance on of torso accelerations to achieve cart motion. Strategies used here by experienced workers were suggestive of a lower risk for WRLBDs, though the level of such risk appeared low or moderate and the group-level differences were not consistent across the conditions examined. Thus, some caution is considered warranted if training programs are developed for WRLBD reduction that incorporate the work methods of experienced workers as a model.

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Chapter 6: Conclusions

Work-related low back disorders (WRLBDs) remain primary concerns in industry, and continue to have a high prevalence and associated costs. Training has been advocated widely as an administrative control to reduce WRLBDs, often in cases where engineering controls, such as modifications of the work and work environment (e.g., tools, work stations, etc.), are not feasible. An intuitively appealing approach to such training, and one that has been proposed by several authors, is using the work methods of experienced workers as a “model” for or “target” of training. Some support for this approach stems from a variety of evidence indicating the existence of distinct work methods used by experienced workers during several occupational tasks. Further, one can presume that experienced workers have developed/adopted efficient work methods and that, in many cases, these methods might be relatively protective (or, reduce WRLBD risks).

More comprehensive knowledge regarding the work methods of experienced workers is required to develop such training, however, since the actual relationships between work experience and WRLBDs remain somewhat unclear. Existing research provides mixed evidence, in that observed differences in work methods related to experience have not been consistent across studies, and similar inconsistencies have been reported as to whether the distinct methods of experienced workers are protective. The current research sought to contribute additional evidence, and focused on two major hypotheses: 1) do distinct work methods exist among experienced workers in a range of occupational tasks; and 2) are these distinct methods are appropriate (i.e., protective) as the bases for training programs to reduce WRLBD risks. Three common occupational tasks were selected and simulated in a laboratory environment in three separate studies: relatively short periods of repetitive lifts/lowers, more extended periods of repetitive lifts/lowers and involving muscular fatigue, and dynamic pushes/pulls.

Work experience was associated with distinct work methods in each study. During short-term repetitive lifts/lowers, distinct work strategies used by experienced workers were characterized by superior balance maintenance and better torso movement stability. Fatigue changed work methods regarding torso kinetics between novices and experienced workers. In both short- and longer-term lift/lower tasks, more flexible work strategies, both between tasks and between participants, was a common aspects among experienced workers. Pushing/pulling resulted in relatively small group-level differences in work methods overall, though higher hand forces and lower torso kinematics/kinetics were evident among experienced workers. From these findings, and consistent with earlier evidence, differences in work methods related to work experience appear to depend substantially on specific tasks and task configurations.

As a whole, the current results suggest that the work methods of experienced workers are unlikely to consistently reduce WRLBD risks. Higher torso kinetics were evident among experienced workers during both short- and longer-term repetitive lifts/lowers, yet the opposite pattern was evident during dynamic pushing/pulling. These results, and similar inconsistencies in existing literature, suggest that training programs incorporating the work methods of experienced workers may not be consistently effective at WRLBD reduction. Future studies are clearly needed, in particular to identify in which tasks or task configurations the work methods of experienced workers might be an appropriate and effective training model.

Several potential limitations in the current work should be noted, and which can serve to guide such future studies. The simulated occupational tasks employed here may be insufficient to completely characterize and/or identify the effects of work experience. As noted above, differences in work methods related to work experience are likely task-specific, and only a few conditions were examined here. Furthermore, experienced workers in the current studies were recruited from several work sites, and the tasks simulated here may be unfamiliar work environments for some of the task configurations. The small sample sizes used here may lead to failure to detect relatively subtle aspects of the work methods of both novices and experienced workers. A range of dependent measures were obtained, though identifying specific level of injury risks remains difficult. Additional measures may be of benefit in future studies, for understanding the effects of experience on injury risks, whether specifically WRLBDs or more generally.

In summary, the main goals of this research were to identify and quantify the distinct work methods used by experienced workers during several common occupational tasks, and to assess whether such differences were associated with difference WRLBD risks. Differences in the work methods adopted by experienced workers were task dependent, and not likely to consistently reduce WRLBD risks. Interventions to control WRLBDs using work methods of experienced workers as a basis for training should be pursued with caution, and should be developed considering the noted task dependency.

Appendices

Appendix A: Informed Consent Form 1

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

Informed Consent for Participants
in Research Projects Involving Human Subjects

<u>Title of Project</u>: Quantifying the effects of experience on motor behaviors during simulated occupational tasks

<u>Investigators</u>: Mr. Jung Yong Lee, Dr. Maury Nussbaum

I. Purpose

The purposes of this proposed project are, in the context of lifting/lowering or pushing/pulling, to identify any differences in physical behaviors between experienced workers and novices. This will be achieved in an experiment involving several simulated occupational tasks in a laboratory setting.

II. Procedures

It is important for you to understand that we are not evaluating you or your performance in any way. You are helping us to collect data that will be used to estimate physical behaviors and loads on the musculoskeletal system during several common occupational tasks. Results from this may help in the future to improve the design such tasks or for training purposes. Any tasks you perform, or opinions you have, will only help us do a better job. Therefore, we ask that you perform normally and be as honest as possible. The information and feedback that you provide is very important to this project. The total experiment time will be approximately 2 hours.

During the course of these experiments, you will be asked to perform the following tasks:

1) Read and sign an Informed Consent Form.
2) Complete paperwork to allow for compensation.
3) Allow experimenters to measure your stature and body weight.
4) Be instructed in isokinetic strength testing and technique.
5) Allow experimenters to restrain your body as needed for strength testing (this will involve fixtures and straps, and will be demonstrated to you first).
4) Be instructed in the experimental tasks (lifting/lowering/pushing/pulling) and techniques.
5) Allow experimenters to place reflective markers over joints and body parts.

6) Perform the experimental tasks with a box or a handcart with mass scaled to your body mass.

This experiment will take place within the Industrial Ergonomics and Biomechanics Laboratory, in the Department of Industrial and Systems Engineering. The experiment will quantify your physical behaviors during simulated occupational tasks (lifting/lowering or pushing/pulling). In order to quantify such behaviors, we need to collect several measures. Prior to experimental sessions, we will ask you for your age and gender, then your stature and body mass will be measured. During a preliminary session, your maximal back muscle strength will be measured using a commercial dynamometer. During experimental sessions, the positions of your body segments will be measured using reflective markers attached to your skin or clothing using double-sided tape, and forces acting on your hands and/or feet will be measured using force platforms and/or load cells. Your heart rate may be monitored using a commercial heart rate monitor during the preliminary and experimental sessions if needed. Experimental tasks may involve muscle fatigue if needed. Sufficient practice and rest periods will be given prior to data collection. Using such data collected, we will use a biomechanical model to quantify your behaviors and/or the presence of muscle fatigue.

III. Risks and Benefits

There are minimal risks to you from participating in this study, which include:

1) minor muscle strain resulting from the experimental tasks (pushing/pulling and repetitive lifting/lowering).
2) delayed onset muscle soreness, in the 24-48 hours following the experiment.
3) minor skin discomfort from surface marker attachment.

Participants in a study are considered volunteers, regardless of whether they receive payment for their participation. Under Commonwealth of Virginia law, workers compensation does not apply to volunteers. Appropriate health insurance is strongly recommended to cover these types of expenses.

This research project will quantify the differences between expert workers and novices in the conduct of simulated occupational tasks. If important differences are found, these may have future benefit in identifying safe working methods and/or the development of worker training methods. While this research may yield such benefits, no promise or guarantee of benefits will be made to participants. Participants may contact the investigators listed at the end of Consent Form to inquire about the results and conclusions of this research.

IV. Extent of Anonymity and Confidentiality

Participant's personal information and identity will be kept in the strictest of confidence. A coding system will be used to associate their identity with individual's data. The list associating names with answers will be destroyed one month after completion of data collection. Photographing might occur for assisting in the assessment of participant's postures. However, any images used in documentation will have faces blacked out to maintain confidentiality. All individual information will be collected in a file and locked when not being used, and experimental data will be stored in password-secured computers. Only the investigators have access to the data. It is possible that the Institutional Review Board (IRB) may view this study's collected data for auditing purposes. The IRB is responsible for the oversight of the protection of human subjects involved in research.

V. Informed Consent

You will receive two informed consent forms to be signed before beginning the experiment; one for your records and one for the experimenter's records.

VI. Compensation

You will be compensated for your participation at a rate of $20 per hour. Compensation will be limited to time spent in the experimental session (e.g., you will not be compensated for your travel to or from the study). Your total payment will vary, depending on the duration required, but the total compensation will be approximately $40.

VII. Freedom to Withdraw

You are free to withdraw from this study at any time without penalty or reason stated, and no penalty or withholding of compensation will occur for doing so. If you choose to withdraw, you will be compensated for the portion of time of the study for which you participated. Furthermore, you are free not to answer any questions or to decline to respond to experimental situations without penalty. There may be circumstances under which the investigator may determine that the experiment should not be continued. In this case, you will be compensated for the portion of the project completed.

VIII. Approval of Research

The Department of Industrial and Systems Engineering has approved this research, as well as the Institutional Review Board (IRB) for Research Involving Human Participants at Virginia Tech.

IX. Participant's Acknowledgments

Check in the box if the statement is true:

- ☐ I have U.S citizenship.
- ☐ I am not under the influence of alcohol or drugs.
- ☐ I have no current or recent (past year) musculoskeletal problems (the experimenter will discuss this with you).

X. Participant's Responsibilities

I voluntarily agree to participate in this study. I have the following responsibilities:

1. To read and understand the aforementioned instructions

2. To answer questions, surveys, etc. honestly and to the best of my ability
3. Be aware that I am free to ask questions or terminate participation at any point time

XI. Participant's Permission
I have read and understand the Informed Consent and conditions of this research project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent for participation in this project.

If I participate, I reserve the right to withdraw at any time without penalty. I agree to abide by the responsibilities noted above, to the best of my ability, or to inform the investigators if I am unable to comply with these.

____

Participant's Signature   Date

____

Experimenter's Signature   Date

Should I have any pertinent questions about this research or its conduct, and research subjects' rights, and whom to contact in the event of a research-related injury to the subject, I may contact:

Jung Yong Lee — 540-986-8712/ jungyong@vt.edu
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David M. Moore — 540-231-4991/moored@vt.edu
Chair, Virginia Tech Institutional Review Board — Telephone/e-mail
for the Protection of Human Subjects
Office of Research Compliance
2000 Kraft Drive, Suite 2000 (0497)
Blacksburg, VA 24061

Appendix B: Informed Consent Form 2

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

Informed Consent for Participants
in Research Projects Involving Human Subjects

Title of Project: Quantifying the effects of experience on motor behaviors during simulated occupational tasks

Investigators: Mr. Jung Yong Lee, Dr. Maury Nussbaum

I. Purpose

The purposes of this proposed project are, in the context of lifting/lowering or pushing/pulling, to identify any differences in physical behaviors between experienced workers and novices. This will be achieved in an experiment involving several simulated occupational tasks in a laboratory setting.

II. Procedures

It is important for you to understand that we are not evaluating you or your performance in any way. You are helping us to collect data that will be used to estimate physical behaviors and loads on the musculoskeletal system during several common occupational tasks. Results from this may help in the future to improve the design such tasks or for training purposes. Any tasks you perform, or opinions you have, will only help us do a better job. Therefore, we ask that you perform normally and be as honest as possible. The information and feedback that you provide is very important to this project. The total experiment time will be approximately 2 hours.

During the course of these experiments, you will be asked to perform the following tasks:

1) Read and sign an Informed Consent Form.
2) Complete paperwork to allow for compensation.
3) Allow experimenters to measure your stature and body weight.
4) Be instructed in isokinetic strength testing and technique.
5) Allow experimenters to restrain your body as needed for strength testing (this will involve fixtures and straps, and will be demonstrated to you first).
4) Be instructed in the experimental tasks (lifting/lowering/pushing/pulling) and techniques.
5) Allow experimenters to place reflective markers over joints and body parts.

6) Perform the experimental tasks with a box or a handcart with mass scaled to your body mass.

This experiment will take place within the Industrial Ergonomics and Biomechanics Laboratory, in the Department of Industrial and Systems Engineering. The experiment will quantify your physical behaviors during simulated occupational tasks (lifting/lowering or pushing/pulling). In order to quantify such behaviors, we need to collect several measures. Prior to experimental sessions, we will ask you for your age and gender, then your stature and body mass will be measured. During a preliminary session, your maximal back muscle strength will be measured using a commercial dynamometer. During experimental sessions, the positions of your body segments will be measured using reflective markers attached to your skin or clothing using double-sided tape, and forces acting on your hands and/or feet will be measured using force platforms and/or load cells. Your heart rate may be monitored using a commercial heart rate monitor during the preliminary and experimental sessions if needed. Experimental tasks may involve muscle fatigue if needed. Sufficient practice and rest periods will be given prior to data collection. Using such data collected, we will use a biomechanical model to quantify your behaviors and/or the presence of muscle fatigue.

III. Risks and Benefits

There are minimal risks to you from participating in this study, which include:

1) minor muscle strain resulting from the experimental tasks (pushing/pulling and repetitive lifting/lowering).
2) delayed onset muscle soreness, in the 24-48 hours following the experiment.
3) minor skin discomfort from surface marker attachment.

Participants in a study are considered volunteers, regardless of whether they receive payment for their participation. Under Commonwealth of Virginia law, workers compensation does not apply to volunteers. Appropriate health insurance is strongly recommended to cover these types of expenses.

This research project will quantify the differences between expert workers and novices in the conduct of simulated occupational tasks. If important differences are found, these may have future benefit in identifying safe working methods and/or the development of worker training methods. While this research may yield such benefits, no promise or guarantee of benefits will be made to participants. Participants may contact the investigators listed at the end of Consent Form to inquire about the results and conclusions of this research.

IV. Extent of Anonymity and Confidentiality

Participant's personal information and identity will be kept in the strictest of confidence. A coding system will be used to associate their identity with individual's data. The list associating names with answers will be destroyed one month after completion of data collection. Photographing might occur for assisting in the assessment of participant’s postures. However, any images used in documentation will have faces blacked out to maintain confidentiality. All individual information will be collected in a file and locked when not being used, and experimental data will be stored in password-secured computers. Only the investigators have access to the data. It is possible that the Institutional Review Board (IRB) may view this study's collected data for auditing purposes. The IRB is responsible for the oversight of the protection of human subjects involved in research.

V. Informed Consent

You will receive two informed consent forms to be signed before beginning the experiment; one for your records and one for the experimenter's records.

VI. Compensation

You will be compensated for your participation at a rate of $10 per hour for pushing/pulling tasks or $20 per hour for lifting/lowering tasks. Compensation will be limited to time spent in the experimental session (e.g., you will not be compensated for your travel to or from the study). Your total payment will vary, depending on the duration required, but the total compensation will be approximately $20 or $40 accordingly.

VII. Freedom to Withdraw

You are free to withdraw from this study at any time without penalty or reason stated, and no penalty or withholding of compensation will occur for doing so. If you choose to withdraw, you will be compensated for the portion of time of the study for which you participated. Furthermore, you are free not to answer any questions or to decline to respond to experimental situations without penalty. There may be circumstances under which the investigator may determine that the experiment should not be continued. In this case, you will be compensated for the portion of the project completed.

VIII. Approval of Research

The Department of Industrial and Systems Engineering has approved this research, as well as the Institutional Review Board (IRB) for Research Involving Human Participants at Virginia Tech.

IX. Participant's Acknowledgments

Check in the box if the statement is true:

- ☐ I have U.S citizenship.
- ☐ I am not under the influence of alcohol or drugs.
- ☐ I have no current or recent (past year) musculoskeletal problems (the experimenter will discuss this with you).

X. Participant's Responsibilities

I voluntarily agree to participate in this study. I have the following responsibilities:

4. To read and understand the aforementioned instructions
5. To answer questions, surveys, etc. honestly and to the best of my ability

6. Be aware that I am free to ask questions or terminate participation at any point time

XI. Participant's Permission

I have read and understand the Informed Consent and conditions of this research project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent for participation in this project.

If I participate, I reserve the right to withdraw at any time without penalty. I agree to abide by the responsibilities noted above, to the best of my ability, or to inform the investigators if I am unable to comply with these.

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Participant's Signature Date

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Experimenter's Signature Date

Should I have any pertinent questions about this research or its conduct, and research subjects' rights, and whom to contact in the event of a research-related injury to the subject, I may contact:

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