Effects of Localized Muscle Fatigue on Postural Control: Interactive Effects with Inclined Surfaces and Unexpected Loads, and Intervention Efficacy

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ABSTRACT

Falls in the workplace are a major cause of injuries and fatalities. Muscle fatigue is one important factor that has been linked to a decrement in postural control and a potential increased falling risk. However, potential interactive effects of muscle fatigue with other risk factors remain unclear, and practical interventions are needed to mitigate the adverse effects of muscle fatigue. The current work was conducted to address these research needs through three experimental studies.

The first study investigated how muscle fatigue affects postural control during quiet standing on inclined surfaces. Inclined surfaces compromised postural control, with the most deleterious effects found while standing in a lateral direction. Fatigue did not result in further decrements in postural control during standing on inclined surfaces.

The second study investigated the effects of muscle fatigue on postural control while lifting unexpected loads. Lifting an object with unexpected mass compromised postural control, with a more substantial effect found in the unexpectedly light load condition. Fatigue-related effects were not consistent, though there was evidence that lumbar muscle fatigue did not compound the adverse effects of lifting an object in unexpected mass conditions.

The last study evaluated the efficacy of three interventions (two auditory stimulations and periodic rest breaks) at mitigating the adverse effects of muscle fatigue on postural control. Allowance of rest breaks did not improve postural control during the fatiguing work, though it was indicated that benefits may be present for some individuals. Both a static pure tone and moving conversation appeared to offset fatigue-induced postural instability.

The current research provides a more comprehensive understanding of the contribution of muscle fatigue to fall risks during occupationally relevant tasks and assessed the efficacy of practical interventions to reduce the risk of falls. These findings may facilitate the development of strategies to prevent occupational falls related to muscle fatigue, inclined surfaces, and manual material handling tasks.

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Chapter 1 Introduction

Falls in the workplace are a major cause of injuries and fatalities. Occupational fatalities involving falls have remained the second most frequent fatal event since 1999 (BLS, 2007a), second only to highway incidents. In 2006, falls accounted for 14% of all occupational fatalities (BLS, 2007a). For nonfatal cases involving days away from work, falls were the third most common cause, accounting for 234,450 (20%) of 1,183,500 injuries and illnesses in 2006 (BLS, 2007b).

In addition to this high incidence rate, falls have great impacts on personal and societal costs as well as workers' health. Annual direct costs of occupational injuries from falls have been estimated to be about $6 billion in the US (Courtney et al., 2001). During the decade ending in 2002, the total cost of fall-related fatal injuries was estimated to be between $69 million and $3 billion, depending on specific industry sectors (NIOSH, 2006). In 2006, the median number of days away from work due to falls was 10 days, and almost 32% of falls resulted in 31 or more days away from work (BLS, 2007b). Occupational falls were found to be associated with the most severely disabling fractures, which resulted in median days away from work as long as 3 months (Courtney and Webster, 1999).

Existing evidence suggests that multiple, diverse factors contribute to occupational falls. Primary causes are thought to be slips, trips, and imbalance episodes, which can be considered collectively as loss of balance incidents (Hsiao and Simeonov, 2001). Postural control is a complex motor skill/process used to maintain balance, which involves multiple sensory systems (visual, vestibular, and proprioceptive/somatosensory), motor control, and central nervous system (CNS) integration (Horak, 2006; Punakallio, 2005; Riley et al., 1998; Umphred, 2001). Impaired postural control, often inferred by increased postural sway, has been shown repeatedly to be associated with an increased falling risk (Baloh et al. 1995; Fernie et al. 1982; Lichtenstein et al. 1988; Maki et al. 1990; Prieto et al. 1996) and predictive of future falls among older individuals (Bergland and Wyller 2004; Pajala et al. 2008; Stel et al. 2003). Thus, postural control plays an important role in preventing falls in the workplace, specifically ensuring that balance control is optimized and/or not compromised.

A number of risk factors that may compromise postural control have been identified and categorized as environmental factors, task-related factors, and personal factors (Hsiao and Simeonov, 2001). Among them, muscle fatigue is one important task-related factor that has been linked to a decrement in postural control and a potential increased risk of falling. Numerous studies have reported increases in postural sway during quiet standing with localized muscular fatigue (LMF). Such an effect has been evident at diverse locations, including the ankle (Corbeil et al. 2003; Lundin et al. 1993; Ochsendorf et al. 2000; Vuillerme et al. 2001; Yaggie and McGregor 2002), lower back (Davidson et al. 2004; Pline et al. 2006; Vuillerme et al. 2007), shoulder (Nussbaum 2003), and neck (Gosselin et al. 2004; Schieppati et al. 2003; Vuillerme et al. 2005). Existing studies have also suggested a decreased ability to recover from a postural perturbation following fatigue. For example, LMF at lumbar extensors and ankle plantar flexors was found to increase center of mass (COM) excursion following a postural perturbation, and also tended to decrease the maximum perturbation that could be withstood without stepping (Davidson, 2007).

Although the adverse effects of muscle fatigue on postural control have been well documented, there is little evidence regarding potential interactive effects of muscle fatigue and other fall risk factors. By far, the majority of existing studies investigating the effects of muscle fatigue on postural control have involved quiet standing on a flat surface. However, there are many occupational settings that require workers to perform tasks on inclined surfaces. Furthermore, balance appears to be compromised when lifting a load with unknown mass, a situation that arises in such jobs as refuse collecting and luggage handling (Commissaris and Toussaint, 1997; de Looze et al., 2000). It remains unclear whether muscle fatigue interacts with inclined surfaces and lifting of unexpected loads to affect postural control, and determining such interactive effects was one of the central focuses of this dissertation.

In addition to these fundamental limitations in our understanding of the effects of work tasks on postural control and potential falls, practical interventions are needed that can mitigate the adverse effects of muscle fatigue. Two fundamental forms of control measures are used to reduce fall-related injuries: fall protection and prevention. Fall protection aims to protect fallers by minimizing injury severity after the initiation of a fall, whereas fall prevention seeks to control the initiation of a fall. Current measures, such as implementation of safety regulations and safety equipment, focus more on fall protection rather than prevention (Hsiao and Simeonov, 2001). Due to negligence, incorrect use, lack of availability, performance or peer pressures, etc., fall protection is not likely to be completely effective at reducing fall injuries. Thus, there is a need for practical interventions to prevent occupational falls, or at least to reduce the risks of these events. Developing and evaluating such interventions was the second central focus of this dissertation.

This dissertation addressed the above-mentioned research needs through three experimental studies. Experiment 1 investigated how muscle fatigue affects postural control during quiet standing on inclined surfaces. Experiment 2 determined the effects of muscle fatigue on postural control while lifting unexpected loads. Experiment 3 evaluated three interventions (two auditory stimulations and periodic rest breaks) for improving postural control during fatiguing physical activities. Each of these three experiments was designed to accomplish a distinct specific aim as follows:

SPECIFIC AIM 1: To investigate the main and interactive effects of inclined surfaces and muscle fatigue on postural control during quiet upright stance. Muscle fatigue was induced by having subjects perform repetitive isotonic exercises involving the lumbar extensors. Three inclination directions were assessed (sagittal ascending, sagittal descending, and lateral), at three inclination angles within each (representing common roof pitches).

SPECIFIC AIM 2: To investigate the effects of muscle fatigue on postural control while lifting an object with unexpected mass. Muscle fatigue was induced by having subjects perform repetitive isotonic exercise using the lumbar extensors. Symmetric lifting of unexpectedly heavy and unexpectedly light objects was performed. Kinematic and kinetic measures were used to evaluate postural control.

SPECIFIC AIM 3: To evaluate the efficacy of three interventions at mitigating the adverse effects of muscle fatigue on postural control. The first two interventions involved auditory inputs, specifically a static pure tone and dynamic background general conversation (removal of the latter is the potential intervention). The third intervention used periodic rest breaks scheduled according to subjectively perceived decrements of postural stability.

> Repetitive lifting was performed for prolonged periods at exertion levels that induced muscle fatigue. Both objective measures and subjective assessments of perceived postural stability were obtained during fatiguing work at fixed intervals.

The results from this dissertation research were intended to facilitate a more comprehensive understanding of the contribution of muscle fatigue to fall risks during occupationally relevant tasks and to help identify effective practical interventions to reduce the risk of falls. The remainder of this dissertation is organized as follows. Chapter 2 describes the interactive effects of lumbar muscle fatigue and surface inclination on postural control. Chapter 3 describes the interactive effects of lumbar muscle fatigue and lifting of unexpected loads on postural control. Chapter 4 describes the efficacy of three interventions at mitigating the adverse effects of muscle fatigue on postural control. A summary of the major findings and suggestions for future work are provided in Chapter 5.

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Chapter 2: Effects of lumbar extensor fatigue and surface inclination on postural control during quiet stance

2.1 Abstract

A number of work environments require workers to perform tasks on inclined surfaces. Such tasks, along with muscle fatigue, can impair postural control and lead to increased falling risks. The objective of this study was to determine the effects of surface inclination angle, inclination direction, and lumbar extensor fatigue on postural control during quiet standing. A group of 18 young healthy participants were tested while standing on inclined surfaces before and after lumbar extensor fatiguing (induced by repetitive isotonic exercise). Three inclination angles (0°, 18°, and 26°) and three inclination directions (sagittal ascending, sagittal descending, and lateral) were examined. Postural control was assessed using several measures derived from center-of-pressure time series and subjectively perceived stability. Significant main effects of inclination angle, direction, and fatigue were observed on most of the dependent measures. The adverse effects of standing on inclined surfaces were found to differ between the three standing directions. In general, a dose-response relationship with inclination angle was most evident in the lateral direction, but least evident in the sagittal descending direction. No fatigue-related interactive effects were evident, suggesting that the adverse effect of lumbar extensor fatigue on postural control was independent of inclination angle and direction. These findings may facilitate the development of fall prevention interventions for work involving inclined surfaces.

Keywords: postural control, muscle fatigue, inclination, falls

2.2 Introduction

Falls in the workplace are a major cause of injuries and fatalities. In 2006, falls remained the second most common cause of occupational fatalities, and accounted for 14% fatal occupational injuries in the United States (BLS, 2007a). For nonfatal cases involving days away from work, falls were the third most common cause, accounting for 234,450 (20%) of 1,183,500 injuries and illnesses in 2006 (BLS, 2007b). It has been suggested that loss of balance incidents (slips, trips, and imbalance) are the primary reasons for occupational falls, and a number of risk factors that can compromise balance have been identified (Hsiao and Simeonov, 2001).

Muscle fatigue is one important factor that has been linked to a decrement in postural control and a potential increased risk of falling. The adverse effects of localized muscle fatigue (LMF) on postural control have been well documented for a range of body locations, including the ankle (Corbeil et al. 2003; Lundin et al. 1993; Ochsendorf et al. 2000; Vuillerme et al. 2001; Yaggie and McGregor 2002), lower back (Davidson et al. 2004; Pline et al. 2006; Vuillerme et al. 2007), shoulder (Nussbaum 2003), and neck (Gosselin et al. 2004; Schieppati et al. 2003; Vuillerme et al. 2005). Existing studies have also suggested a decreased ability to recover from a postural perturbation following fatigue. For example, LMF at the lumbar extensors and ankle plantar flexors was found to increase center of mass (COM) excursion following a postural perturbation, and also tended to decrease the maximum perturbation that could be withstood without stepping (Davidson, 2007). However, the majority of existing studies investigating the effects of muscle fatigue on postural control have involved quiet standing on a horizontal surface. Many occupational settings, however, require workers to perform tasks on inclined surfaces.

Inclined surfaces have been associated with an increased risk of slipping due to the increased friction demands. Zhao et al. (1987) investigated the effects of inclined surfaces on slipping risk during a lifting task. Inclined surfaces increased tangential/normal force ratio, indicating increased friction requirements, and subjective ratings also increase with surface inclination. During walking up- and down-slope, peak required coefficient of friction was found to increase from 0.15 on a horizontal surface to over 0.6 on a 20 ° inclined surface, and was consistently higher (i.e., increased risk of slipping) when walking up-slope (McVay and Redfern, 1994).

Limited evidence is available regarding the effects of inclined surfaces on postural control. Decreased postural stability, as indicated by increased postural sway has been found with increased surface inclination (Simeonov et al., 2003). Bhattacharya et al. (2002/2003) evaluated postural stability while performing simulated industrial tasks on inclined and elevated surfaces under various environmental conditions, and found that standing on inclined surfaces increased postural sway during stationary standing and bending tasks. In contrast to such evidence regarding the effects of inclination angle, there is relatively little evidence regarding the differential effects of inclination direction. Standing on inclined surfaces in different directions results in altered joint positions and motions (e.g., at the ankle, knee, and hip) and muscle activation patterns (Mezzarane and Kohn, 2007; Sasagawa et al., 2009), both of which have a direct impact on afferent feedback and hence postural control. To the author’s knowledge, only one relevant study has been conducted (Mezzarane and Kohn, 2007), which compared the effects of two sagittal inclination directions (sagittal ascending vs. sagittal descending) on postural control. Their results indicated that the ascending direction led to higher postural instability, as indicated by higher spectral amplitudes of postural sway at lower frequencies (< 0.3 Hz) in the antero-posterior direction. Simeonov et al. (2009) examined the effects of inclination in the semi-lateral direction and reported increases in postural sway across diverse conditions (with/without vision, elevated surface, and with a visual reference). The effect of lateral inclination on postural control remains unclear, as are the relative effects of differing inclination directions.

This study had two goals. The first was to determine whether there are interactive effects of lumbar extensor fatigue and inclination on postural control during quiet standing. The second was to identify whether there are differential effects of three inclination directions on postural control. It was hypothesized that: 1) lumbar extensor fatigue would magnify the adverse effects of standing on inclined surfaces, and 2) larger inclination angles would have more substantial adverse effects on postural control, and that these effects would depend on inclination direction. Results from this work were intended to facilitate the development of strategies to prevent occupational falls related to work on inclined surfaces and in the presence of muscle fatigue.

2.3 Methods

2.3.1 Participants

Eighteen participants were recruited from the University and local community, with equal numbers of males and females. All participants were 18 to 24 years old, which was intended to represent individuals near the typical beginning of working life and to control for potential effects of age on outcomes of interest. Mean (SD) age, stature, and body mass of the male participants were 21.4 (1.5) yr, 177.4 (7.1) cm, and 76.1 (8.1) kg, respectively, with corresponding values of 21.4 (2.0) yr, 161.8 (7.7) cm, and 61.4 (8.9) kg for the female participants. Participants had no self-reported injuries, musculoskeletal disorders, neurological disorders, vestibular disease, or occurrences of falls in the past 12 months. This experiment was approved by the Virginia Tech Institutional Review Board, and participants provided informed consent prior to participation.

2.3.2 Experimental Design

A full factorial repeated-measure design was employed with three independent variables: inclination angle, inclination direction, and fatigue. Each participant completed three experimental sessions with a minimum of two days between sessions to avoid residual effects of fatigue. Participants were exposed to one inclination angle in each session; this was done for efficiency, specifically to avoid the need to change inclinations angles within a session. The order of angle presentations was counterbalanced using Latin squares. Each session consisted of several pre-fatigue trials of quiet standing, warm-up exercises, maximum voluntary isokinetic contractions (MVIC), fatiguing isotonic exercises, and several post-fatigue trials of quiet standing.

Independent Variables

Inclination angle (A): Three inclination angles were evaluated: horizontal (0°), 4/12 (~18°), and 6/12 (~26°). The 4/12 represents a low-slope type, and 6/12 is classified as steep (OSHA, 1995). These two slopes were selected because they represent a range of common surface slopes on which workers frequently perform roofing tasks without any additional support devices (Simeonov et al., 2003). The horizontal surface served as a control condition. Specific inclination angles were achieved using three plywood structures placed over a force platform (AMTI OR6-7-1000, Watertown, MA, USA). Each platform had the same height at the center to reduce potential confounding effects of elevation on postural control.

Inclination direction (D): The effects of inclination direction (Figure 2.1) were evaluated at three levels: sagittal ascending (D1), sagittal descending (D2), and lateral (D3). The first two directions involved the participant respectively facing “uphill” or “downhill”. For the lateral direction, participants stood on the inclined platforms with their dominant foot in the lower position. Effects of the other lateral direction (D4), wherein participants stood on the inclined platforms with their non-dominant foot in the lower position, were only included during the pre-fatigue condition.

Sagittal ascending (D1)

Sagittal descending (D2)

Lateral (D3)
Dominant foot in the lower position

Lateral (D4)
Non-dominant foot in the lower position

Figure 2.1 Inclination directions

Fatigue (F): Muscle fatigue was induced by having participants perform repetitive isotonic exercises using the lumbar extensors. This muscle group was selected since a previous study indicated that fatigue of the lumbar extensors had more substantial adverse effects on postural control versus fatigue at the ankle, knee, or shoulder (Lin et al., 2009). Fatigue had two levels: pre-fatigue and post-fatigue.

2.3.3 Experimental Procedures

Participants completed 12 pre-fatigue trials of quiet standing involving three consecutive trials in each of the four inclination directions (D1, D2, D3, and D4). Presentation order of inclination direction was randomized. Between trials, roughly one minute of seated rest was provided to reduce possible after-effects of standing on inclined surfaces and the development of fatigue. Each trial lasted 70 sec, during which participants stood on the plywood platform with their feet together, arms by their sides, head pointed straight ahead, and eyes closed. For the lateral direction, participants were required to maintain an extended knee posture in the "downhill" leg. Participants were instructed to "concentrate on standing as still as possible" and to think about their level of "perceived stability" during the period of the quiet standing. After each trail, participants provided a rating of perceived stability as described below. Each participant wore the same shoes across three experimental sessions.

After the pre-fatigue standing trials, participants performed warm-up activities consisting of two sets of 10 unloaded torso flexions. Subsequently, MVICs involving lumbar extension were conducted at a speed of 60 °/s using a dynamometer (Biodex 3 Pro, Biodex Medical Systems Inc., Shirley, New York, USA). A specially-constructed fixture was used to partially isolate the lumbar extensors. MVICs were performed through a 45 °range of motion (ROM), starting from 45 °flexion to the neutral upright position. Participants were instructed to perform the exertions "as hard and as fast as possible" and were given non-threatening verbal encouragement during these and the subsequent fatiguing exercises. At least five MVICs were performed with a minimum of one minute of rest between each. MVICs were recorded as the peak torques after adjustment for gravitational effects on body segment and dynamometer attachments masses. If an increasing trend in peak torque was evident at the fifth MVIC, additional MVICs were performed until performance stabilized.

Fatigue was induced using repetitive isotonic lumbar extensions at 60% of the highest observed MVIC torque, through the same ROM as in the MVIC trials. These exertions were performed at 12 repetitions/min and minimal resistance was applied when the joint was returning to its original position. Participants were instructed to start the exertions at the sound of an audio tone, and to try to reach the end range of motion at the sound of the second tone; these procedures were used to ensure that the exertions were performed at a consistent repetition rate and angular velocity. After two minutes of exercise, another MVIC was performed. If the resulting peak torque was greater than the pre-fatigue MVIC, the isotonic exertions were adjusted to be 60% of the new value. This process was repeated again after 10 minutes of exercise if participants had not exhibited signs of fatigue. Isotonic exercises were continued until participants could not complete exertions over the entire ROM for three consecutive repetitions, at which point they were assumed to be fatigued to ~60% of their baseline isokinetic capacity.

Following the fatiguing exercises, a single MVIC was conducted to determine the extent of fatigue. Immediately after this, three trials of quiet stance on the inclined or horizontal platforms were conducted with a rest break of one minute between each. This set of procedures (fatiguing exercises, follow-up MVIC, and three trials of quiet stance) was replicated three times, once for each of the three inclination directions (D1, D2, and D3). The order of presentation of the three inclination directions was the same for both pre- and post-fatigue trials.

Triaxial ground reaction forces and moments were sampled at 120 Hz from the force platform during the quiet stance trials. The raw signals were low-pass filtered (Butterworth, 5 Hz cut-off frequency, 2nd order, bi-directional), and transformed to obtain center-of-pressure (COP) time series (Winter, 2004). For COP calculations, the reference frame was associated with the inclined platform not the gravitational vector. Thus, the *z* axis was perpendicular to the inclined platform, and the orthogonal axes (*x* and *y*) were on the inclined platform surface. For each standing trial, the initial and final five seconds of data were removed to avoid initial transients and termination anticipation effects, respectively.

2.3.4 Dependent Measures

From the COP time series obtained in each trial, mean velocity (MV) and sway area (SA) were determined (Prieto et al. 1996). A fractal measure derived from detrended fluctuation analysis (DFA exponent) was also calculated (Delignieres et al. 2003), since previous work has suggested that this measure is more sensitive than traditional measures to factors thought to affect postural control (Norris et al., 2005). DFA exponents are measures of long-range dependence (persistence or anti-persistence) in a time series, and values vary between 0 and 2. If the signal behaves as fractional Gaussian noise (fGn), DFA exponents range from 0 to 1. If the signal behaves as fractional Brownian motion (fBm), DFA exponents range from 1 to 2. When DFA < 0.5 or 1 < DFA < 1.5, the signal is anti-persistent and smaller DFA represents more anti-persistence. When 0.5 < DFA < 1 or 1.5 < DFA < 2, the signal is persistent and larger DFA represents more persistence (Delignieres et al., 2003; Delignieres et al., 2006; Norris et al., 2005). Some diversity exists regarding how these exponents are to be practically interpreted. However, Collins et al. (1995) have suggested that greater persistence of the COP series is correlated with increased muscle activity and decrements in postural stability. Greater anti-persistence has been suggested to reflect a more tightly controlled postural system (Amoud et al., 2007). This set of COP-based measures was intended to provide a comprehensive assessment of postural control. Mean velocity and DFA exponent were determined in both the antero-posterior (AP) and medio-lateral (ML) directions.

To supplement the objective (COP-based) measures, subjective perceptions of postural stability were obtained. Perceived stability (PS) was assessed based on the procedures described by Schieppati et al. (1999). Participants were asked to evaluate their stability by indicating how stable they felt during quiet standing immediately after each trial. A rating scale ranging from 0 to 100 was used, where 0 indicated that participants did not feel stable at all, and 100 indicated that they felt completely stable. Prior to the pre-fatigue standing trials in each session, participants were "calibrated" to the two extremes of the scale. For the lower extreme (0), they adopted a unilateral stance with eyes closed. For the upper extreme (100), they stood with eyes open while holding a rigid object.

2.3.5 Statistical Analysis

Preliminary analyses were conducted to investigate whether there were potential confounding effects related to treatment order. A one-way repeated-measures analysis of variance (RANOVA) was used to determine if pre-fatigue MVIC differed between sessions. Fatigue extent was determined as the percent change in MVIC [(pre - post)/pre], and two-way (inclination angle and inclination direction) RANOVAs were performed on this and exercise duration (endurance, or time to task failure).

We assumed that the two lateral inclination directions (D3 and D4) had similar effects on postural control, since the human body is bilaterally symmetrical. To confirm this assumption, three-way (inclination angle, inclination direction, and trial) RANOVAs were performed on all dependent variables obtained during pre-fatigue trials.

Since three pre-fatigue and three post-fatigue quiet standing trials were performed in each combination of inclination angle and direction, differences among trials might be present due to adaptation to the inclined surfaces or recovery from fatigue. To identify if order-related effects were present, three-way (inclination angle, inclination direction, and order) RANOVAs were performed on all dependent variables, separately for the pre-fatigue and post-fatigue trials. Significant order effects were found on pre-fatigue MV_{AP} and DFA_{AP} ($p < 0.046$), and on post-fatigue bilateral MV and SA ($p < 0.0001$). Tukey's Honestly Significant Difference (HSD) tests indicated that the last pre-fatigue trial had significantly smaller MV_{AP} and larger DFA_{AP} than the first pre-fatigue trial. MV and SA of the first post-fatigue trial were significantly larger than the other two post-fatigue trials. Thus, only the last pre-fatigue and the first post-fatigue trials were examined in the following analyses.

Three-way RANOVAs were performed to determine the effects of inclination angle, inclination direction, and fatigue on each dependent measure. MV_{ML}, MV_{AP}, and SA were log-transformed to achieve normally distributed residuals, though summary statistics are given in the original units. Effect sizes (η^2) of the main and interactive effects were calculated from the estimated variance components and were interpreted using the following criteria: ~0.01 small, ~0.06 medium, and ~0.14 large (Cohen, 1988). Where relevant, *post hoc* comparisons were conducted using Tukey's HSD. The level of significance for all tests was set at $p < 0.05$, and all statistical analyses were performed using JMP 8.0 (SAS Inc., Cary, NC, USA). Summary results are presented as means (SD).

2.4 Results

2.4.1 Assessment of Potential Confounding Effects

No significant inclination angle (session) effect was found on pre-fatigue MVICs ($p = 0.76$), and differences between levels were quite small (~1.7%). Overall, MVICs decreased by 25.3% (19.2%) after fatiguing exercise, and exercise duration was 5.3 (6.3) minutes. Inclination angle and inclination direction had no significant main or interaction effects on fatigue extent or exercise duration ($p > 0.11$). The corresponding effect sizes were quite small, ranging from 0.003 to 0.021. These results suggest minimal confounding effects related to fatigue differences between treatments.

2.4.2 Lateral Direction Effects

No significant difference was observed between the two lateral directions (D3 and D4) on any of the dependent variables ($p > 0.1$). The effect sizes of the main and interaction effects of direction were consistently quite small, in the range of 0 ~ 0.004. These results support our initial assumption that the two lateral inclination directions had similar effects on postural control.

2.4.3 Main Effects

ANOVA results are summarized in Table 2.1. Main effects of inclination angle were significant for all dependent variables and had large effect sizes. Relative to the horizontal condition, the 18 ° angle (4/12 slope) resulted in a 35.6% increase in MV_{ML}, a 36.1% increase in MV_{AP}, a 43.0

increase in SA, a 4.0% decrease in DFA_{ML}, a 5.6% decrease in DFA_{AP}, and a 19.7% decrease in PS. The 26 ° angle (6/12 slope) had more substantial effects, with a 71.0% increase in MV_{ML}, an 86.3% increase in MV_{AP}, a 107.2% increase in SA, a 5.9% decrease in DFA_{ML}, a 9.4% decrease in DFA_{AP}, and a 38.3% decrease in PS. Fatigue of the lumbar extensors significantly increased MV_{ML} (18.2%), MV_{AP} (27.3%), and SA (41.9%), and decreased PS (8.1%). The magnitude of fatigue effects ranged from small to medium. Significant main effects of inclination direction were observed on all dependent variables except for MV_{AP}, with effect sizes that ranged from small to large. These main effects of inclination direction, however, were overshadowed by substantial interactions with inclination angle as summarized below.

Table 2.1 Summary of ANOVA results (p-values) and effect sizes (η^2), for the effects of inclination angle, inclination direction, and fatigue on several measures of postural control. The symbol * indicates a significant effect ($p < 0.05$).

Measures		Angle (A)	Direction (D)	Fatigue (F)	A × D	A × F	D × F	A × D × F
MV_{ML}	p	<.0001*	<.0001*	<.0001*	<.0001*	0.87	0.58	0.71
	η^2	0.21	0.18	0.038	0.11	0.00	0.001	0.001
MV_{AP}	p	<.0001*	0.29	<.0001*	0.036*	0.62	0.14	0.33
	η^2	0.32	0.002	0.072	0.009	0.001	0.003	0.004
SA	p	<.0001*	<.0001*	<.0001*	<.0001*	0.54	0.23	0.43
	η^2	0.17	0.052	0.073	0.026	0.001	0.003	0.003
DFA_{ML}	p	<.0001*	0.023*	0.073	0.15	0.83	0.71	0.66
	η^2	0.18	0.013	0.006	0.012	0.001	0.001	0.004
DFA_{AP}	p	<.0001*	0.0003*	0.15	0.22	0.28	0.69	0.29
	η^2	0.29	0.021	0.003	0.007	0.003	0.001	0.006
PS	p	<.0001*	<.0001*	0.0001*	<.0001*	0.93	0.51	0.93
	η^2	0.32	0.024	0.015	0.024	0.000	0.001	0.001

2.4.4 Interaction Effects

Significant interactive effects of inclination angle × inclination direction were observed on MV_{ML}, MV_{AP}, SA, and PS (Figure 2.2), and with effect sizes ranging from small to medium. On the horizontal surface (0°), there were no significant differences between the three directions for any of the postural control measures ($p > 0.45$).

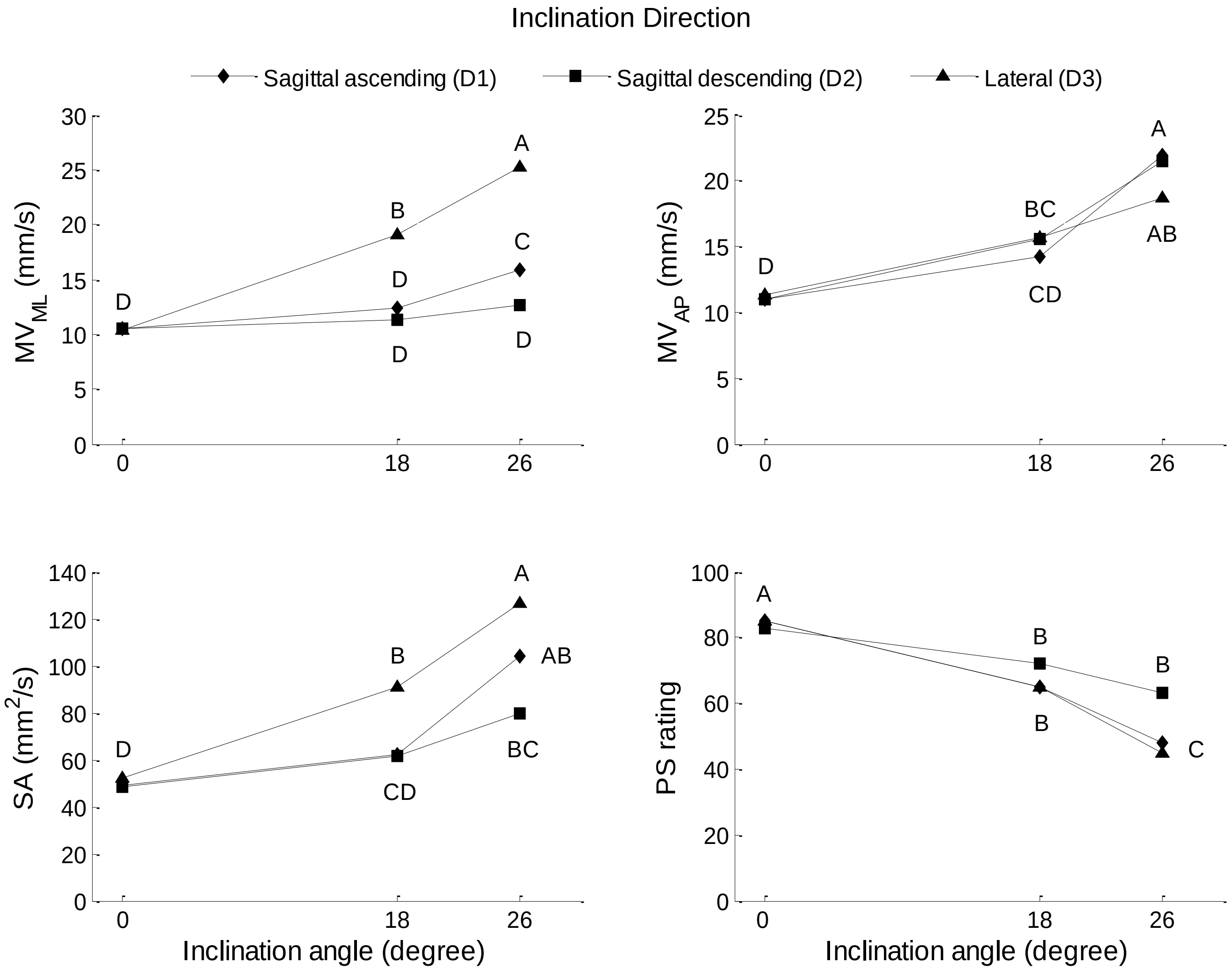

Figure 2.2 Interactive effects of inclination angle and inclination direction on mean velocity in the ML and AP directions (MV$_{ML}$ and MV$_{AP}$), sway area (SA), and perceived stability (PS). Pairs of values with different letters are significantly different. Errors bars not shown for clarity (SD range = 2.2 ~ 7.6 mm/s for MV$_{ML}$, 3.2 ~ 12.3 mm/s for MV$_{AP}$, 23.2 ~ 91.0 mm^2/s for SA, and 9 ~ 27 for PS).

In the 18 °inclination condition, the lateral direction (D3) resulted in significantly larger MV$_{ML}$ and SA compared to the two sagittal directions (D1 and D2), while there were no differences in these measures between D1 and D2. No significant direction effect was evident on MV_{AP} and PS at the 18 ° inclination.

In the 26 ° inclination condition, MV_{AP} was not significantly affected by inclination direction. The lateral direction led to the largest values of MV_{ML} and SA, and the smallest PS, followed by sagittal ascending direction. In all three inclination directions, larger inclination angles resulted in larger MV_{ML}, MV_{AP}, and SA, and smaller PS. With respect to MV_{ML}, SA, and PS, the strongest dose-response relationship with inclination angle was evident in the lateral direction, and the weakest in the sagittal descending direction. Effects of inclination angle were generally consistent across inclination directions for MV_{AP}. No significant inclination angle × fatigue or inclination direction × fatigue interaction effects were found, and effect sizes for these were consistently quite small.

2.5 Discussion

The current study aimed to determine whether lumbar muscle fatigue interacted with inclined surfaces to affect postural control and also whether the effects of inclination on postural control differed among three standing directions. Lumbar muscle fatigue was expected to magnify the adverse effects of standing on inclined surfaces, yet no fatigue-related interactive effects were found. Together with the significant and substantial main effects of fatigue, this lack of interactive effects suggests that the adverse effect of lumbar extensor fatigue on postural control was independent of inclination angle and direction. The adverse effects of standing on inclined surfaces were found to differ between three standing directions and also varied depending on the specific postural control measure used. For MV_{ML}, SA, and PS, a dose-response relationship with inclination angle was most evident in the lateral direction and least evident in the sagittal descending direction. For MV_{AP}, the effects of inclination angle were generally consistent across inclination directions.

Although a number of studies have demonstrated impaired postural control during quiet stance and recovery from a postural perturbation following LMF at several body locations, none to our knowledge has investigated whether there are interactive effects of LMF and inclination. Our results showed that there was no difference in the adverse effects of lumbar extensor fatigue among different inclination angles and directions. While the study may have been underpowered, the consistently small effect size for fatigue relative interactive effects argues for a small influence. A lack of fatigue related interactive effects could also be attributed to an insensitivity of the postural control measures used. However, these measures have been repeated shown to be sensitive to a wide range of individual differences and sensory and environmental manipulations.

The current fatiguing protocol may also not have been sufficient to induce decrements in postural control beyond those imposed by surface inclination. This protocol was intended to fatigue each participant to the same relative level, specifically 60% of pre-fatigue MVIC, yet the average MVIC decrease was only 25.3% (19.2%). Perturbations to postural control induced by this fatigue magnitude were likely compensated by an effective reweighting of sensory inputs. Simeonov et al. (2003) suggested that observed increases in COP velocity and high frequency components while on inclined surfaces reflected an enhancement use of somatosensory information from the distal lower extremity to facilitate postural control. If so, this implies that standing on inclined surfaces leads to an increased reliance on plantar cutaneous sensation. Under the current experiment conditions, plantar cutaneous sensation likely remained unaltered, and thus could still provide sufficiently accurate information for the postural control system to compensate the perturbation induced by lumbar muscle fatigue during standing on the inclined surfaces.

Clear differential effects of inclination directions were found, with the lateral direction showing the most substantial effects on postural control based on both objective and subjective measures (Figure 2.2). A major difference between the lateral and sagittal standing directions was the postural asymmetry required in the former. Although we did not measure the actual body weight distribution between the two legs in the lateral condition, it seems reasonable that the "downhill" leg acting as the supporting leg would bear more body weight compared to the "uphill" leg. Thus, the asymmetrical body weight distribution likely contributed to the more substantial effects of lateral inclination. Asymmetrical weight distribution has also been shown to impair postural control during quiet stance on horizontal surfaces (Anker et al., 2008; Blaszczyk et al., 2000; Genthon and Rougier, 2005).

To our knowledge, no prior work has investigated the effects of lateral inclination. The nearest comparable work was by Simeonov et al. (2009), who used a semi-lateral direction. They found that such a situation had more substantial effects on ML vs. AP postural control (based on increased in COP RMS distance). This is consistent with our findings, in which the increases in MV_{ML} induced by the lateral inclination direction were larger than MV_{AP}. These directional differences can also be ascribed to the asymmetrical body weight distribution in the lateral inclination condition. During quiet standing on a horizontal surface, an asymmetrical weight distribution has larger effects on sway in the ML direction (Anker et al., 2008; Genthon and Rougier, 2005). Further, postural control in the ML direction during quiet stance is primarily organized and controlled by the hip load/unload strategy achieved using the hip abductors/adductors (Winter, 1996). Thus, an asymmetrical weight distribution, considered as a perturbation of the hip load/unload mechanism, logically induces larger increases in the ML direction.

Regarding the two sagittal inclination directions, the ascending direction resulted in larger postural sway than the descending direction. Mezzarane and Kohn (2007) similarly found that the ascending direction induced a higher instability, as reflected in the higher spectral amplitudes of COP at lower frequencies (< 0.3Hz). However, these authors also reported that the sagittal descending direction had lower spectral amplitudes of COP at lower frequencies than the horizontal condition, suggesting that the sagittal descending direction was more stable than the horizontal condition. In contrast, we found that both sagittal directions induced postural instability, a discrepancy that may be attributed to the smaller inclination angle (14°) employed in the prior study. Here, the adverse effects of the sagittal descending direction were the weakest among all the non-horizontal conditions (Figure 2.3), with significant differences found only in MV_{AP} and PS at the 18° inclination angle; thus, the smaller angle (14°) in Mezzarane and Kohn's study might have been insufficient to induce significant changes.

Several mechanisms may be responsible for the differential effects found between the two sagittal directions. Different ankle muscle activity resulted from either lengthening (ascending) or shortening (descending) the ankle plantarflexors is likely to be one contributing factor. Mezzarane and Kohn (2007) found that soleus activity increased in the descending direction, but was unaffected in the ascending direction, whereas Sasagawa et al. (2009) reported increased soleus activity in the descending direction but decreased activity in the ascending direction. Proprioceptive acuity of the involved muscles may also differ between directions (due to differences in spindle length). Mezzarane and Kohn (2007) suggested that the differential spatial activation of plantar afferents imposed by the two sagittal directions could result in distinct postural responses and thereby account for such directional effects. However, further work is needed to confirm the exact contributing factors.

Dose-response effects of inclination angle on postural control were evident in all three inclination directions. Such dose-response relationships have been reported in several studies (Bhattacharya et al., 2002/2003; Simeonov et al., 2003; Simeonov et al., 2009) using a variety of postural control measures, across several age groups, and in diverse experimental conditions (with/without vision, on elevated surfaces). Simeonov et al. (2003) suggested that inclination alters somatosensory input as a result of modified postural alignment and reduced effective base of support. Inclination angle further influences the length of the ankle muscles, due to the plantarflexion/dorsiflexion or inversion/eversion, which in turn affects ankle muscle stiffness and activity. This combination of effects on somatosensation and muscular state are likely to be important contributors to the dose-response relationship between inclination angle and postural control, though the exact underlying mechanism(s) remains unclear and further studies are needed.

Fatigue-related decrements in postural control found here were comparable to an earlier study using the same fatiguing protocol (Lin et al., 2009). The underlying mechanisms accounting for the effects of LMF on postural control have not been fully elucidated. One likely contributing factor is impaired proprioceptive acuity of the lumbar spine (Taimela et al., 1999) and the ankle (Pline et al., 2005) induced by lumbar extensor fatigue. Davidson et al. (2004) indicated that such impaired proprioception could delay stabilizing muscle activation and lead to decrements in postural control. Furthermore, due to reduced proprioception at the lumbar spine and ankle, the CNS may reweight sensory inputs to achieve more effective control of balance (Horak, 1996; Oie et al., 2002). Specifically, Vuillerme and Pinsault (2007) reported an increased reliance on somatosensory inputs from the foot and ankle following lumbar extensor fatigue. Using results from model-based simulations, such reweighting processes (loss/restoration of accurate sensory information) have the potential to disturb postural stability (Peterka and Loughlin, 2004).

One potential concern is a gender difference in fatigability of the lumbar extensors (Larivière et al., 2006). To address this, unpaired *t*-tests were performed on the percent change in MVIC and exercise duration to assess gender differences related to the fatiguing exercises. Strength decreases were comparable between the two genders ($p = 0.71$), with mean decreases of 26.6% for males and 24.2% for females. Although females exhibited a longer exercise duration (7.3 vs. 3.3 min), this difference was not significant ($p = 0.082$). Additional analyses were performed by including gender in the ANOVAs used to assess the effects of inclination angle, inclination direction, and fatigue on each of the dependent measures. Consistent with earlier evidence of gender differences (Era et al., 1997; Juntunen et al., 1987), significantly higher COP-based measures were evident among males, and is likely attributable to anthropometry (Era et al., 1996). Several significant interaction effects with gender were also evident. Overall, the effects of inclination angle and fatigue were larger among males. The larger decrements in postural control among males post-fatigue may be due to larger absolute decreases in lumbar extensors strength, since the relative strength decrement was comparable for the two gender groups and males had larger pre-fatigue values. Qualitatively, however, the main and interactive effects of the primary independent variable were quite similar for both genders.

Several limitations of the current research should be noted. First, falling risk or propensity for loss of balance was not directly measured, but postural control was instead evaluated under controlled and quasi-static conditions. However, several of the COP-based measured used here have been demonstrated as valid indices of risk of falling in the existing literature (e.g., Fernie et al., 1982; Lafond et al., 2004; Lichtenstein et al., 1988; Maki et al., 1990; Nardone et al., 2006). Second, the reliability of the dependent measures may be a concern. Only one quiet standing trial was analyzed in both pre- and post fatigue conditions due to the observed trial order effects. However, it has been suggested that even for the most reliable COP-based measure (mean velocity), two trials are needed to achieve excellent reliability using the current trial duration of 60 seconds (Lafond et al., 2004). Third, postural control was measured with a constrained stance (standing with feet together), which is not typical in occupational settings or daily life. Stance width has been demonstrated to influence postural control, with a wider stance leading to less postural sway (Day et al., 1993; Kirby et al., 1987). Fourth, generalization of the current findings requires some cautions. The current study used a very controlled fatigue procedure, and future studies should be conducted to determine whether comparable effects result from additional or more complex fatigue conditions and fatigue of other muscle groups. Generalization to other populations was also limited, since only young healthy participants were recruited in this study. The effects of inclination and lumbar extensor fatigue will likely differ in an older population or among those with pathological conditions.

The results of this study have several practical implications. The differential effects of inclination directions suggests that tasks performed on laterally inclined surfaces may lead to a higher falling risk than those on the sagittally inclined surfaces, and that work involving such lateral conditions should be particularly avoided. Given the increasingly detrimental effect of inclination angle on postural control, working surfaces should be horizontal where possible, or minimized otherwise. Localized muscle fatigue compromised postural control, and may increase falling risks. Further, this effect appears to be consistent across a range of task conditions, suggesting that fatigue should be minimized regardless of the specific task demands or environment. Task redesign may be possible to achieve these recommendations, or education and training programs may be of use to facilitate an appreciation of the higher risks involved in the noted working conditions.

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Chapter 3: Effects of lumbar extensor fatigue on postural control while lifting an unexpected load

3.1 Abstract

The objectives of this study were to compare the effects of lifting an unexpectedly heavy and light object on postural control and also whether the effects of unexpected loads were magnified by localized muscle fatigue. A group of 16 young healthy participants were randomly assigned to one of two actual lifting conditions (light or heavy load), with half of participants assigned and gender balanced in each. Each participant performed three sets of repetitive lifting tasks, two before and one after exercise-induced fatigue of the lumbar extensors. A sudden change in the mass of the lifted object mass was induced in the first and third lifting sets. Postural control was assessed using several measures derived from center-of-mass (COM) and center-of-pressure (COP) time series. Lifting an object with unexpected mass compromised postural control, with a more substantial effect found in the unexpectedly light load condition. Fatigue-related effects were not consistent, with the results suggesting that lumbar muscle fatigue did not compound the adverse effects of lifting an object in unexpected mass conditions. These findings may facilitate the development of injury prevention interventions for work involving manual material handling tasks.

Keyword: postural control, muscle fatigue, lifting, unexpected load, falls

3.2 Introduction

As described in Chapter 2, occupational falls are a major cause of injuries and fatalities, and loss of balance incidents (slips, trips, and imbalance) are thought to be the primary proximal causes (Hsiao and Simeonov, 2001). Balance is maintained through the postural control system, involving multiple sensory systems (visual, vestibular, and proprioceptive/somatosensory), motor control, and central nervous system integration (Horak, 2006; Punakallio, 2005; Riley et al., 1998; Umphred, 2001). Perturbations to any of these aspects can potentially have adverse effects on postural control. Localized muscle fatigue (LMF) is one important risk factor, given that it leads to changes in muscle contractile efficacy (Gandevia, 2001), peripheral proprioception (Allen and Proske, 2006; Bjorklund et al., 2000; Lee et al., 2003; Pline et al., 2005), and central control (Taylor et al., 2000). Although the adverse effects of LMF on postural control have been well documented (summarized in Chapter 2), most existing studies have focused on assessing postural control during quiet standing. In the occupational setting, however, workers perform tasks that are often more dynamics, for example those involving manual materials handling (MMH).

MMH can be expected to challenge postural control, and increase the risk of occupational falls. There is some supporting epidemiological evidence, specifically that falls from elevations and on the same level typically occur in the roofing industry when carrying heavy and bulky materials on slippery and inclined working surfaces (Fredericks et al., 2005). Holding or carrying loads changes the configuration of the masses and the location of the resulting center-of-mass (COM) that has to be controlled, and thus directly affects reactive and proactive control of balance. Due to the multi-link structure of the human body, any voluntary movement will impose a perturbation of balance (Kollmitzer et al., 2002). Such a perturbation may increase when the movement is performed with an added load, such as during MMH activities. A number of factors relevant to MMH have been identified as influencing postural control, such as load position and stability (Lee and Lee, 2002), lifting technique (Toussaint et al., 1997), stance condition (Kollmitzer et al., 2002), and unexpected loads (Chow et al., 2003; Commissaris and Toussaint, 1997; van der Burg et al., 2000). The latter was the focus of the current study.

Unexpected loads can result from the sudden application or release of a load, or an incorrect estimation of the mass of an object. Sudden release of a load during lifting can threaten postural control. Chow et al. (2003) investigated the effects of sudden release of a load at two release heights during stoop lifting. Their findings indicated that sudden release at a lower height significantly increased postural disturbance, which was quantified using COP trajectories. In another study, Chow et al. (2004) investigated the effect of fatigue on the muscular and postural response to sudden release of lifting loads. Their results suggested that there was a tradeoff between maintaining postural stability and preventing the trunk musculature from overloading the spine in response to a sudden release of load. In their study, however, no evidence was found to support that fatigue could increase the risk of falling following sudden release.

Load knowledge is also important for postural control during lifting. A correct estimation of the load mass allows for adequate programming of anticipatory postural adjustments. Successful prediction can lead to smooth and accurate performance of the task, whereas if the prediction is inaccurate, loss of balance and consequent falls can occur (Toussaint et al., 1998). Several studies have examined the effects of load knowledge on postural control and the risk of falling. Commissaris and Toussaint (1997) assessed how load knowledge affected low back loading and postural control during lifting tasks. In their study, overestimation of a load during lifting caused a disturbance of balance in 92% trials. van der Burg et al. (2000) examined the effects of underestimation of load mass on balance and low back loading, and found that lifting an unexpectedly heavy object did not cause loss of balance. However, the risk of balance loss did increase, since the angular momentum of the whole body COM was significantly less compared to condition involving correct estimation of load mass. A smaller angular momentum implies that preparatory movements were not sufficient to counteract the disturbing effect of lifting a heavy object; instead, it was programmed for a light object. Although both overestimation and underestimation of lifting load have been demonstrated to compromise postural control, due to the different experimental protocols it is difficult to compare directly the effects of overestimation and underestimation on postural control.

This study had two goals. The first was to compare the effects of lifting an unexpectedly heavy and light object on postural control. The second was to investigate the effects of muscle fatigue on postural control during lifting an object with unexpected mass. It was hypothesized that: 1) lifting an object with unexpected load mass would have deleterious effects on postural control compared to the lifting of an expected mass, and that effects of unexpectedly heavy and unexpectedly light would differ, and 2) lumbar muscle fatigue would exacerbate the adverse effects of lifting an unexpected load. Results from this work were intended to provide fundamental evidence on the effects of muscle fatigue on postural control during relatively realistic load lifting tasks and facilitate the development of strategies to prevent occupational falls related to work involving lifting unexpected loads in the presence of muscle fatigue.

3.3 Methods

3.3.1 Participants

Sixteen participants from the University and local community completed the study, with equal numbers of males and females. All participants were 18 to 24 years old, which was intended to represent individuals near the typical beginning of working life and to control for potential effects of age on the outcomes of interest. Mean (SD) age, stature, and body mass of the male participants were 20.8 (2.1) yr, 179.3 (3.4) cm, and 75.2 (5.7) kg, respectively, with corresponding values of 22.5 (1.9) yr, 161.2 (5.3) cm, and 56.6 (5.6) kg for the female participants. Participants had no self-reported injuries, musculoskeletal disorders, neurological disorders, vestibular disease, or occurrences of falls in the past 12 months. They were also required to have moderate levels of physical activities. All completed an informed consent procedure approved by the University Institutional Review Board.

3.3.2 Experimental Design

A mixed-factor design experiment was conducted with three independent variables: fatigue, expectation of object mass, and actual object mass. Participants were randomly assigned to one of two actual lifting conditions (either light or heavy load), with half of participants assigned to each. Thus, each participant was only exposed to one unexpected load (either unexpectedly light or unexpectedly heavy) to minimize potential learning effects following initial exposure to an unexpected load. Each participant completed one experimental session, which consisted of three sets of lifting tasks, with two before fatigue and one after fatigue. A sudden change of lifting object mass was induced in the first and third lifting sets.

Independent Variables

Fatigue: Muscle fatigue was a within-subject factor with two levels (pre-fatigue and post-fatigue). Fatigue was induced by having participants perform repetitive isotonic exercise using the lumbar extensors.

Expectation of object mass: Expectation was manipulated as a within-subject factor with two levels (expected and unexpected).

Actual object mass: Actual object mass was a between-subject factor with two levels (light and heavy). Participants were randomly assigned to one of the two levels with gender balanced in each. A box ($0.60 \times 0.40 \times 0.23$ m) with mass ~3kg was used as the light load. An electromagnetic (S-251512-12, Magnetech Corp, Novi, MI, USA) was attached under the box, by which a 10 kg iron bar could be attached to or released from the box without participants' notice. Power to the electromagnetic was controlled remotely using a silent hand switch. The box plus the iron bar was considered as the heavy load (total mass = 13 kg).

3.3.3 Experimental Procedures

Upon arrival, each participant completed an informed consent procedure and a screening questionnaire including identifying information, demographic data, and health condition. Once the eligibility of participants was confirmed, height and mass of each participant were obtained. Then, several practice lifting trials were conducted with both the light and heavy loads to familiarize participants with the task.

During lifting tasks, participants stood on a force platform (AMTI OR6-7-1000, Watertown, MA, USA) and lifted the box from a shelf set 0.19 m above the floor and in front of them (Figure 3.1). A metal barrier was placed behind the box to ensure safety. Participants were asked to lift the box from the shelf to their knuckle height. A back lift or stoop technique (legs remain extended during the movement) was required, to minimize potential confounding effects induced by different lifting techniques, to increase the task challenge, and with a goal of isolating fatigue to the lumbar extensors. Pacing was controlled using an acoustic metronome. Participants were instructed to start the lifting from the upright standing posture at the sound of an audio tone and to complete one lift + lower and return to the upright standing posture at the sound of a second tone. Participants were instructed to perform the lift symmetrically (in the sagittal plane), keep both feet on the ground, and ensure their balance throughout the lifting movements. The position of the feet relative to the box and stance width were self-selected by participants during initial practice and were fixed thereafter. Repeatability of foot placement between trials was be maintained by outlining the feet on top of the force platform using tape. To prevent participants from perceiving the actual load mass during the time period between initial grasping of the box and the box lift off, participants were instructed to lift as quickly as possible during the initial part of the lift (Commissaris and Toussaint, 1997; van der Burg et al., 2000).

Figure 3.1 Lifting task and experimental configuration

After the practice lifting trials, participants performed the first lifting set. Those in the light load group first lifted a 13 kg box five times, and then the object mass was decreased to 3 kg at the 6th lifting movement without their notice. Participants in the heavy load group first lifted a 3 kg box five times, and then the load mass was increased to 13 kg at the 6th lifting movement without their notice. Participants were not told how many lifts they were going to perform nor when the mass was going to change; they were only informed (initially) that they would be lifting boxes with different masses. The last lifting movement of the first lifting set was considered the unexpected condition and used for further analysis.

Following the first lifting set, a 5-minute seated rest period was provided. Then, the second lifting set was conducted. Participants in the light load group lifted a 3 kg box five times, and those in the heavy load group lifted a 13 kg box five times. The last lifting movement of the second lifting set was considered the expected condition.

Immediately after the second lifting set, participants performed warm-up activities, maximum voluntary isokinetic contractions (MVICs), isotonic fatiguing exercise, and a single post-fatigue MVIC in sequence. The procedures related to warm-up exercise, MVIC, and fatiguing exercise used in the current study are the same as in Chapter 2. In brief, warm-up activities consisted of two sets of 10 unloaded torso flexions/extensions. MVICs involving lumbar extension were conducted at a speed of 60 °/s using a dynamometer (Biodex 3 Pro, Biodex Medical Systems Inc., Shirley, New York, USA), with a minimum of five replications. Fatigue was induced using repetitive isotonic lumbar extensions at 60% of the highest observed MVIC torque, at a frequency of 12 repetitions/min. Both MVICs and fatiguing exercises were performed through a 45 ° range of motion (ROM), starting from 45 ° torso flexion to the neutral upright position. Fatigue was considered induced when participants could not complete exertions over the entire ROM for three consecutive repetitions, at which point they were assumed to be fatigued to ~60% of their baseline isokinetic capacity.

The third lifting set was conducted immediately following the final MVIC. Participants in the light load group lifted a 13 kg box three times, and then the load mass was decreased to 3 kg at the 4th lifting movement without their notice. Participants in the heavy load group lifted a 3 kg box three times, and then the load mass was increased to 13 kg at the 4th lifting movement without their notice. In both groups, the last lifting movement was regarded as the unexpected condition.

At the end of the experimental session, participants were asked to rate their level of expectation, specifically the degree to which they expected the mass changes that occurred in both the pre-fatigue and post-fatigue conditions. A visual analog scale was used, where the lower extreme (0) indicated that the mass change was completely unexpected, and the upper extreme (100) that the mass change was completely expected. They were also requested not to reveal the experiment procedures to others.

3.3.4 Data Collection and Processing

Triaxial ground reaction forces and moments were sampled at 120 Hz from the force platform during the lifting trials. Raw signals were low-pass filtered (Butterworth, 15 Hz cut-off frequency, 4th order, bi-directional), and transformed to obtain center of pressure (COP) time series (Winter, 2004). Body segment kinematics was monitored using a marker tracking system (Vicon 460 workstation, Vicon Motion Systems Inc., Lake Forest, CA, USA). Passive surface markers (n = 9) were placed unilaterally (left side) over the 5th metatarsal, leateral malleolus, lateral femoral epicodyle, iliac crest, lateral humeral epicondyle, lateral styloid, acromion, cervical (C7), and vertex. Two additional markers were attached over the left toe and heel to determine the base of support. Marker positions were sampled at 120 Hz and low-pass filtered (Butterworth, 15 Hz cut-off frequency, 4nd order, bi-directional).

A 2-D linked segment model was used to calculate the whole body center-of-mass (COM). A total of 7 body segments were defined according to the coordinates of the joint positions in the sagittal plane: foot, lower leg, upper leg, trunk, upper arm, forearm, and head. Segmental masses, COM positions, and moments of inertia were estimated from anthropometric measures using equations provided by de Leva (1996). Angles of each segment were calculated relative to the horizontal. Linear and angular velocities of each segment were determined using numerical differentiation.

For each participant, only three lifting movements were analyzed: 1) the 6th lifting movement in the first lifting set (pre-fatigue, unexpected); 2) the 5th lifting movement in the second lifting set (pre-fatigue, expected); and, 3) the 4th lifting movement in the third lifting set (post-fatigue, unexpected). Each lifting movement was synchronized in time, based on the onset of upward box movement, to allow for averaging of lifting movements across participants (Commissaris and Toussaint, 1997; van der Burg et al., 2000). Movement onset was determined using a second force platform (AMTI OR6-7-1000, Watertown, MA, USA) placed under the shelf and the box. Onset of upward movement ($t = 0$) was defined as the instant when the vertical ground reaction force exceeded 5N. For each lifting movement, a total of 1.5 s was included for analysis (0.5 s before and 1.0 s after movement onset). The data were downsampled to 10Hz, yielding a total of 16 samples (5 and10 after movement onset, and $t = 0$).

3.3.5 Dependent Measures

Dependent variables consisted of several measures derived from COM that have been used to evaluate postural control during lifting (Toussaint et al., 1995):

1. COM_{rel}: The horizontal position of the whole body COM, relative (normalized) to the base of support. Values of 0% and 100% indicate that the COM was located at the heels and toes, respectively.

2. L: The instantaneous linear momentum of the whole body COM in the horizontal (L_{AP}) and vertical directions (L_{Z}), calculated from the linear momenta of each segmental COM:

$$L = \sum_{j=1}^{n} (m_j v_j)$$

where, m_j is the mass of the jth segment, v_j is the linear velocity of the jth segment, and n is the total number of body segments.

3. H: The instantaneous angular momentum of the whole body COM:

$$H = \sum_{j=1}^{n} (I_j \omega_j + m_j r_j \times v_j)$$

where, I_j is the moment of inertia of the jth segment relative to its COM, ω_j is the angular velocity of the jth segment, r_j is the position vector of the jth segmental COM relative to the position of the whole body COM, and v_j is the velocity of the jth segmental COM relative to the whole body COM.

Mean velocity (MV) and ellipse area (EA) were determined (Prieto et al. 1996) from the COP time series, using a 1s window subsequent to lifting onset. Mean velocity was determined in both the antero-posterior (AP) and medio-lateral (ML) directions.

3.3.6 Statistical Analysis

Differences in the distributions of age, body mass, and stature between the two participant groups were examined using unpaired *t*-tests. To investigate whether fatigue extent differed between the two groups, unpaired *t*-tests were conducted on pre-fatigue MVIC, ΔMVIC, and exercise duration (endurance, or time to task failure). Differences in the degree of expectation between groups (light vs. heavy load) and conditions (pre-fatigue vs. post-fatigue) were examined using a two-way mixed-factor ANOVA. Here, and in subsequent analyses, effect sizes

(η^2) were calculated from the estimated variance components and were interpreted using the following criteria: ~0.01 small, ~0.06 medium, and ~0.14 large (Cohen, 1988).

For each 1.5 s lifting movement, the 5 samples before the onset of upward lifting and the 11 samples (including $t = 0$) thereafter were analyzed separately. For COM-based measures, the data obtained before and after the onset of the upward lifting were analyzed separately. To analyze the effects of the two unexpected conditions, three-way mixed-factor ANOVAs were performed on COM-based measures obtained before fatiguing exercise, with the actual object mass (light vs. heavy) as a between-subject variable, and with expectation (expected vs. unexpected) and time as the within-subject variables. Time had five levels (-0.5, -0.4, -0.3, -0.2, and -0.1s) prior to movement onset and 11 levels (0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, and 1.0s) post-onset. For COP-based measures, two-way mixed-factor ANOVAs were performed on the data obtained before fatigue, with the actual object mass as a between-subject variable, and expectation as a within-subject variable.

To investigate the effects of lumbar muscle fatigue on postural responses while lifting an unexpected load, three-way mixed-factor ANOVAs were performed on the COM-based measures obtained from the 1st and 3rd lifting sets. Independent variables were fatigue (pre vs. post), actual object mass (light vs. mass), and time. For COP-based measures, two-way mixed-factor ANOVAs were performed on the data obtained before and after fatigue during the unexpected condition, with the actual object mass as a between-subject variable, and fatigue as a within-subject variable. Where relevant, *post hoc* comparisons were conducted using Tukey's HSD. The level of significance for all statistical tests was set at $p < 0.05$, and all statistical analyses were performed using JMP 8.0 (SAS Inc., Cary, NC, USA). Summary results are presented as means (SD).

3.4 Results

3.4.1 Assessment of Confounding Effects

There were no significant differences in age, body mass, or stature between the two groups ($p > 0.49$, $\eta^2 = 0.018 \sim 0.033$). Participants were fatigued to comparable levels in the two groups, as indicated by non-significant group effects on pre-fatigue MVIC ($p = 0.87$, $\eta^2 = 0.002$) and ΔMVIC ($p = 0.12$, $\eta^2 = 0.17$). However, a borderline effect of group was found on exercise duration ($p = 0.072$) with a fairly large effect size ($\eta^2 = 0.21$). Overall, MVICs decreased by 31.7% (22.1%) after fatiguing exercise, and exercise duration was 8.0 (6.7) minutes. No significant main or interaction effects of group and condition were found on the level of expectation ($p > 0.12$, $\eta^2 = 0 \sim 0.035$), with an overall value of 6.2 (12.1) across groups and conditions.

3.4.2 Effects of Unexpected Load

Effects Prior to Lifting Onset

ANOVA results for COM-based measures obtained before the onset of lifting are summarized in Table 3.1. Prior to lifting onset there were no significant main effects of actual object mass, and the corresponding effects sizes were consistently small. A significant main effect of expectation was found on COM_{rel}, though with a small effect size. Across the two actual object masses, COM_{rel} moved backward to the heels by 4% during the unexpected condition compared to the expected condition. Time significantly affected all measures except for COM_{rel}, with medium to large effect sizes. In the period immediately prior to lifting (-0.3s ~ 0s), COM_{rel} and L_{AP}

decreased, and L_Z and H increased. No evident temporal trend was observed in the period before -0.3s (Figure 3.2).

Table 3.1 Summary of ANOVA results (p – values) and effect sizes (η^2), for the effects of actual object mass (M), expectation (E), and time (T) on COM-based measures *prior to* movement onset. The symbol * indicates a significant effect ($p < 0.05$).

Measures		Mass (M)	Expectation (E)	Time (T)	M × E	M × T	E × T	M × E × T
COM_{rel}	p	0.94	0.0004*	0.94	<.0001*	0.99	0.99	0.90
	η^2	0.00	0.037	0.002	0.101	0.00	0.00	0.003
L_{AP}	p	0.97	0.38	0.0054*	0.231	0.37	0.88	0.07
	η^2	0.00	0.003	0.062	0.009	0.017	0.005	0.036
L_Z	p	0.63	0.18	<.0001*	0.56	0.0008*	0.95	0.006*
	η^2	0.005	0.006	0.195	0.001	0.063	0.002	0.048
H	p	0.42	0.15	<.0001*	0.12	0.026*	0.99	0.11
	η^2	0.021	0.005	0.214	0.006	0.003	0.00	0.018

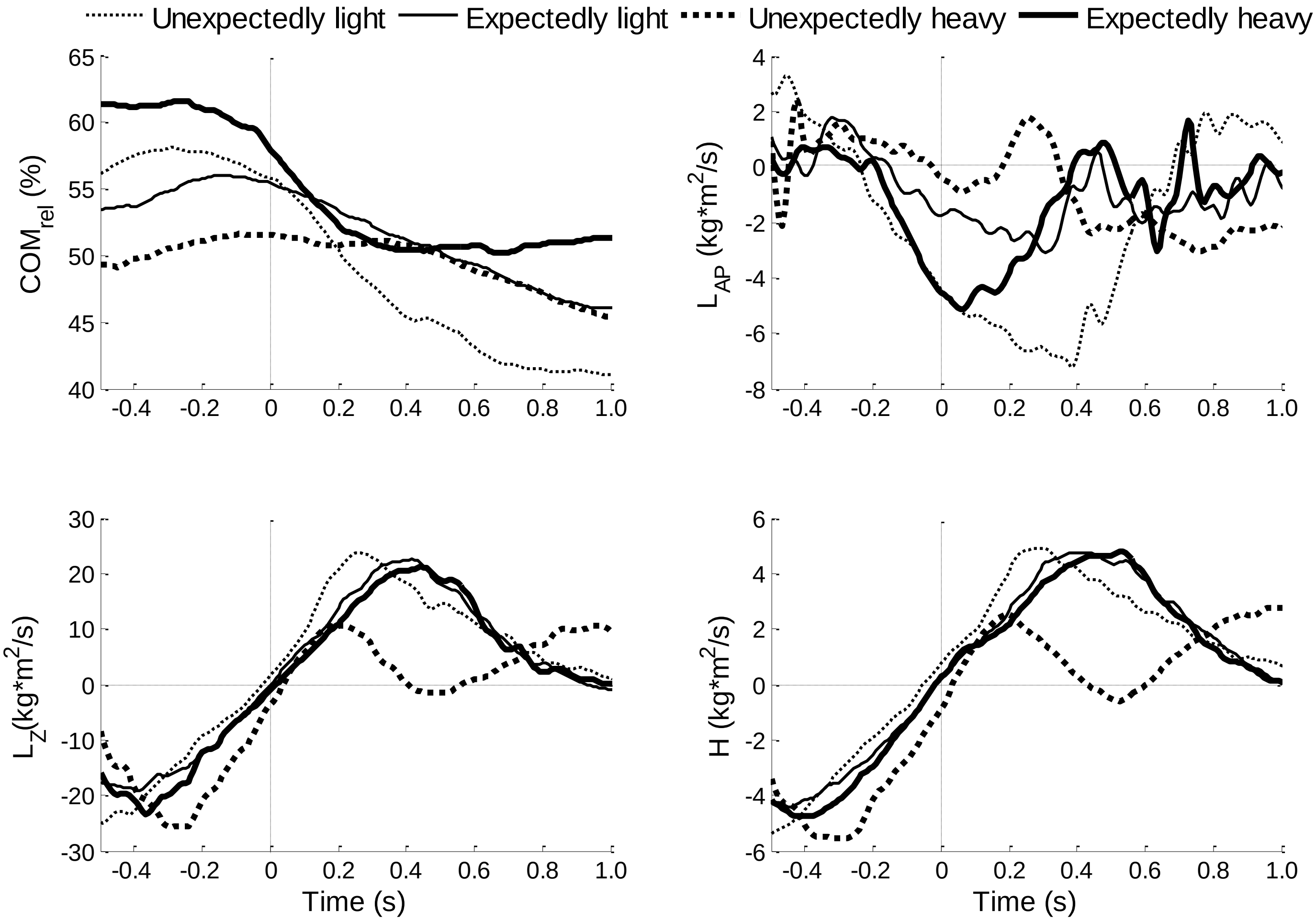

Figure 3.2 Mean pre-fatigue responses prior to and following lifting onset, for relative COM location (COM_{rel}), linear momentum in the horizontal direction (L_{AP}), linear momentum in the vertical direction (L_Z), and angular momentum (H) for the pre-fatigue conditions. Negative values of L_{AP}, L_Z, and H indicate a backward velocity, a downward velocity, and a forward rotation, respectively.

A significant interaction effect of actual object mass × expectation was observed on COM_{rel} (Figure 3.3). No significant difference was found between the unexpected and expected conditions for the light load, though the unexpected condition had a larger COM_{rel}. For the heavy load, COM_{rel} in the unexpected condition significantly shifted backward (toward the heels), by 9.5% compared to the expectedly condition. For the expected condition, the light load was associated with significantly smaller COM_{rel}, whereas a larger COM_{rel} was found for the light load in the unexpected condition.

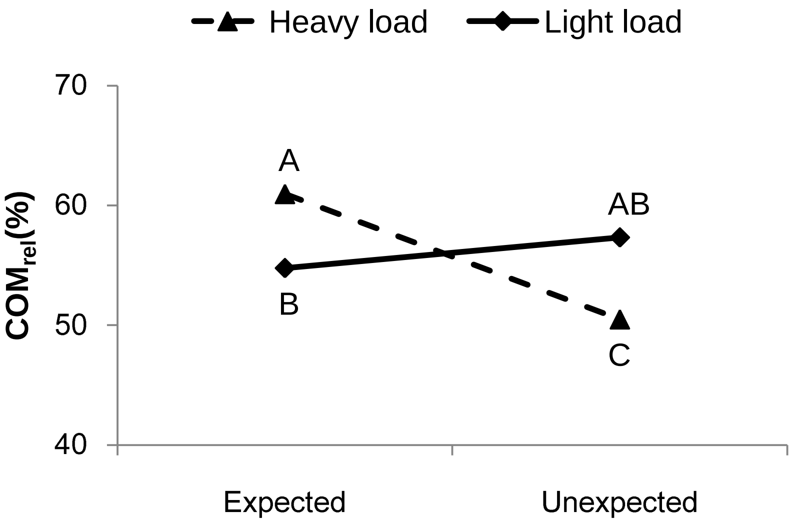

Figure 3.3 Interactive effect of actual object mass and expectation on the mean relative COM location (COM_{rel}) over the 0.5 s prior to lifting onset. Pairs of values with different letters are significantly different. Errors bars not shown for clarity (SD range = 6.9% ~ 11.3%).

Significant interaction effects of actual object mass × time were found on L_Z and H with corresponding effect size ranging from small to medium (Figure 3.2). For the light load, L_Z increased as lifting onset approached. For the heavy load, both L_Z and H decreased initially, reached lowest levels at -0.3s, then increased as movement onset approached.

There were no significant interaction effects of expectation × time on any of the COM-based measures. A second-order interaction effect of actual object mass × expectation × time was found on L_Z. This interaction effect was evident as differences in the temporal patterns occurring before the onset of movement between the expected/unexpected conditions and the light/heavy loads (Figure 3.2).

Effects Following Lifting Onset

ANOVA results for COM-based measures obtained after the onset of lifting are summarized in Table 3.2. Actual object mass had no significant main effects on any of the COM-based measures, though the effect on L_Z was borderline. The corresponding effect sizes were consistently small. Expectation showed significant effects on all measures except for L_{AP}, though with small effect sizes. The unexpected condition had significantly smaller values of COM_{rel}, L_Z, and H. Time significantly affected all measures with effect sizes ranging from medium to large.

Table 3.2 Summary of ANOVA results (p – values) and effect sizes (η^2), for the effects of actual object mass (M), expectation (E), and time (T) on COM-based measures *after* movement onset. The symbol * indicates a significant effect ($p < 0.05$).

Measures		Mass (M)	Expectation (E)	Time (T)	M × E	M × T	E × T	M × E × T
COM_{rel}	p	0.50	<.0001*	<.0001*	0.28	0.51	0.99	0.77
	η^2	0.015	0.033	0.087	0.002	0.013	0.004	0.009
L_{AP}	p	0.12	0.11	0.0007*	0.088	<.0001*	0.068	<.0001*
	η^2	0.015	0.005	0.064	0.006	0.076	0.036	0.129
L_{Z}	p	0.072	0.016*	<.0001*	0.0002*	<.0001*	<.0001*	<.0001*
	η^2	0.03	0.007	0.295	0.017	0.057	0.095	0.045
H	p	0.19	0.0017*	<.0001*	0.0005*	<.0001*	<.0001*	<.0001*
	η^2	0.025	0.012	0.202	0.015	0.047	0.107	0.046

Significant interaction effects of actual object mass × expectation were observed on L_{Z} and H (Figure 3.4). For the light load, no effect of expectation was found on L_{Z}, though larger value occurred in unexpected condition. For the heavy load, the unexpected condition resulted in significantly smaller L_{Z} than in the expected condition. For the expected condition, no difference was found between the two loads, whereas significantly larger L_{Z} was found for the light load in the unexpected condition. The same pattern was evident for H.

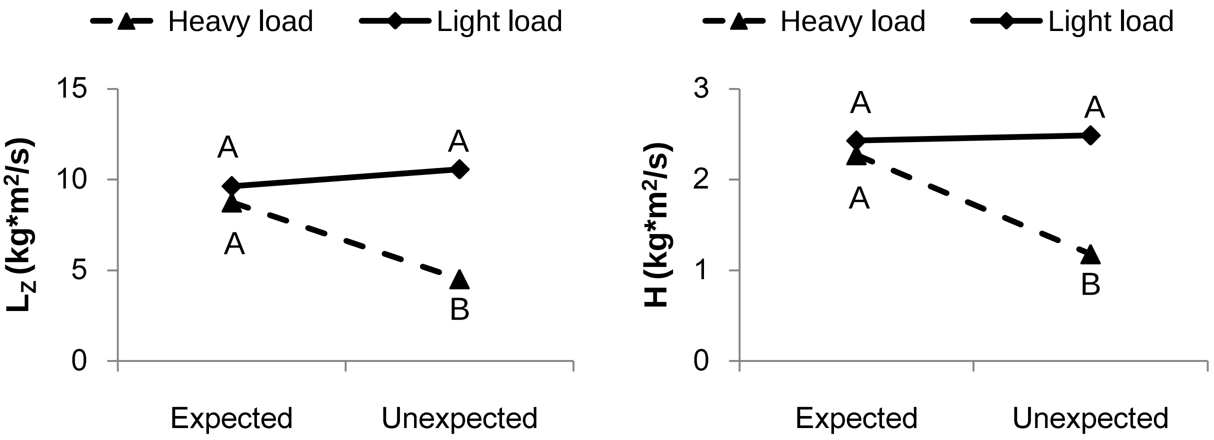

Figure 3.4 Interactive effects of actual object mass and expectation on the mean linear momentum in the vertical direction (L_Z), and mean angular momentum (H) over the 1 s following lifting onset. Pairs of values with different letters are significantly different. Errors bars not shown for clarity (SD range = 2.1 ~ 10.3 kg*m^2/s).

Significant interaction effects of actual object mass × time were found on all measures except for COM_{rel} (Figure 3.2). When a light load was lifted, L_{AP} decreased over the 0.3s immediately following lifting onset and increased afterwards, while an opposite pattern was observed when the heavy load was lifted. For both loads, L_Z and H increased in the initial 0.3s after lifting onset and decreased subsequently. Compared to the heavy load, the light load led to larger values before 0.8s and smaller values after this.

For both L_Z and H, patterns with respect to time differed depending on whether or not the load was expected (i.e., a significant expectation x time interaction). Second order interaction effects of actual object mass × expectation × time were found on all measures except for COM_{rel}. These interaction effects were evident as differences in the temporal patterns occurring following the onset of movement between the expected/unexpected conditions and the light/heavy loads (Figure 3.2).

ANOVA results for COP-based measures are summarized in Table 3.3. No significant effects of actual object mass were found on any of the three COP-based measures, and these were associated with small effect sizes. Expectation had significant effects on MV_{AP} and MV_{ML}, and a borderline effect on EA, with consistently large effect sizes. Compared to the expected condition, the unexpected condition increased EA by 89.4%, MV_{AP} by 71.6%, and MV_{ML} by 32.7%. A significant interaction effect of actual object mass × expectation was found on MV_{AP} with a medium effect size (Figure 3.5). Decomposing this interaction into its simple effects indicated that there was no significant difference between the expectedly heavy and unexpectedly heavy conditions, though a larger MV_{AP} was found in the latter. However, significant differences existed between the expectedly light and unexpectedly light conditions. The unexpectedly light condition increased MV_{AP} by 122% compared to the expectedly light condition. Furthermore, the increase in MV_{AP} induced by the unexpected situation was larger for the light load than the heavy load. Though failing to reach significance, a borderline interaction effect of actual object mass × expectation was observed on EA, with a similar trend that indicated a larger increase induced by a lack of expectation for the light object.

Table 3.3 Summary of ANOVA results (p – values) and effect sizes (η^2), for the effects of actual object mass (M) and expectation (E) on COP-based measures after movement onset. The symbol * indicates a significant effect ($p < 0.05$).

Measures		Mass (M)	Expectation (E)	M × E
EA	p	0.21	0.056	0.075
	η^2	0.04	0.125	0.107
MV_{AP}	p	0.69	<.0001*	0.02*
	η^2	0.005	0.336	0.08
MV_{ML}	p	0.92	0.031*	0.19
	η^2	0.00	0.133	0.045

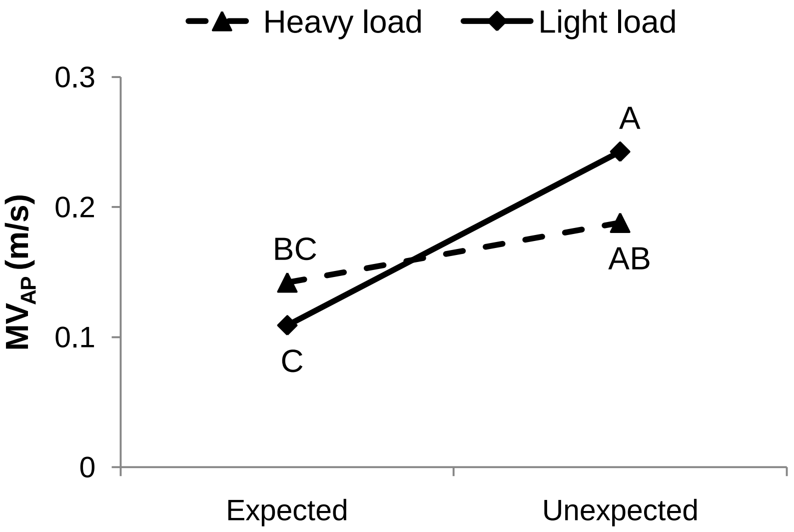

Figure 3.5 Interactive effect of actual object mass and expectation on mean velocity in the AP direction (MV_{AP}). Pairs of values with different letters are significantly different. Errors bars not shown for clarity (SD range = 0.024 ~ 0.10 m/s).

3.4.3 Effects of Fatigue

Effects Prior to Lifting Onset

ANOVA results for COM-based measures obtained before the onset of lifting are summarized in Table 3.4. No significant difference was found between the two actual object mass groups, with small to medium effect sizes. Fatigue significantly affected all COM-based measures except for L_{AP}, and the corresponding effect sizes were small to medium. After fatigue, COM_{rel} moved forward (toward the toes) by 7.7%, and L_{Z} and H increased by 14.5% and 14.6%, respectively. Time significantly affected all COM-based measures except for COM_{rel}, with corresponding effect sizes ranging from small to large (Figure 3.6).

Table 3.4 Summary of ANOVA results (p – values) and effect sizes (η^2), for the effects of actual object mass (M), fatigue (F), and time (T) on COM-based measures before the onset of lifting. The symbol * indicates a significant effect ($p < 0.05$).

Measures		Mass (M)	Fatigue (F)	Time (T)	M × F	M × T	F × T	M × F × T
COM_{rel}	p	0.709	<.0001*	0.98	0.0003*	0.88	0.99	0.99
	η^2	0.002	0.087	0.002	0.046	0.004	0.00	0.001
L_{AP}	p	0.17	0.22	0.0035*	0.082	0.037*	0.82	0.99
	η^2	0.034	0.007	0.078	0.014	0.077	0.007	0.001
L_{Z}	p	0.21	0.028*	<.0001*	0.087	<.0001*	0.92	0.63
	η^2	0.036	0.014	0.037	0.008	0.035	0.001	0.002
H	p	0.14	0.018*	<.0001*	0.33	<.0001*	0.72	0.97
	η^2	0.067	0.012	0.20	0.002	0.071	0.004	0.001

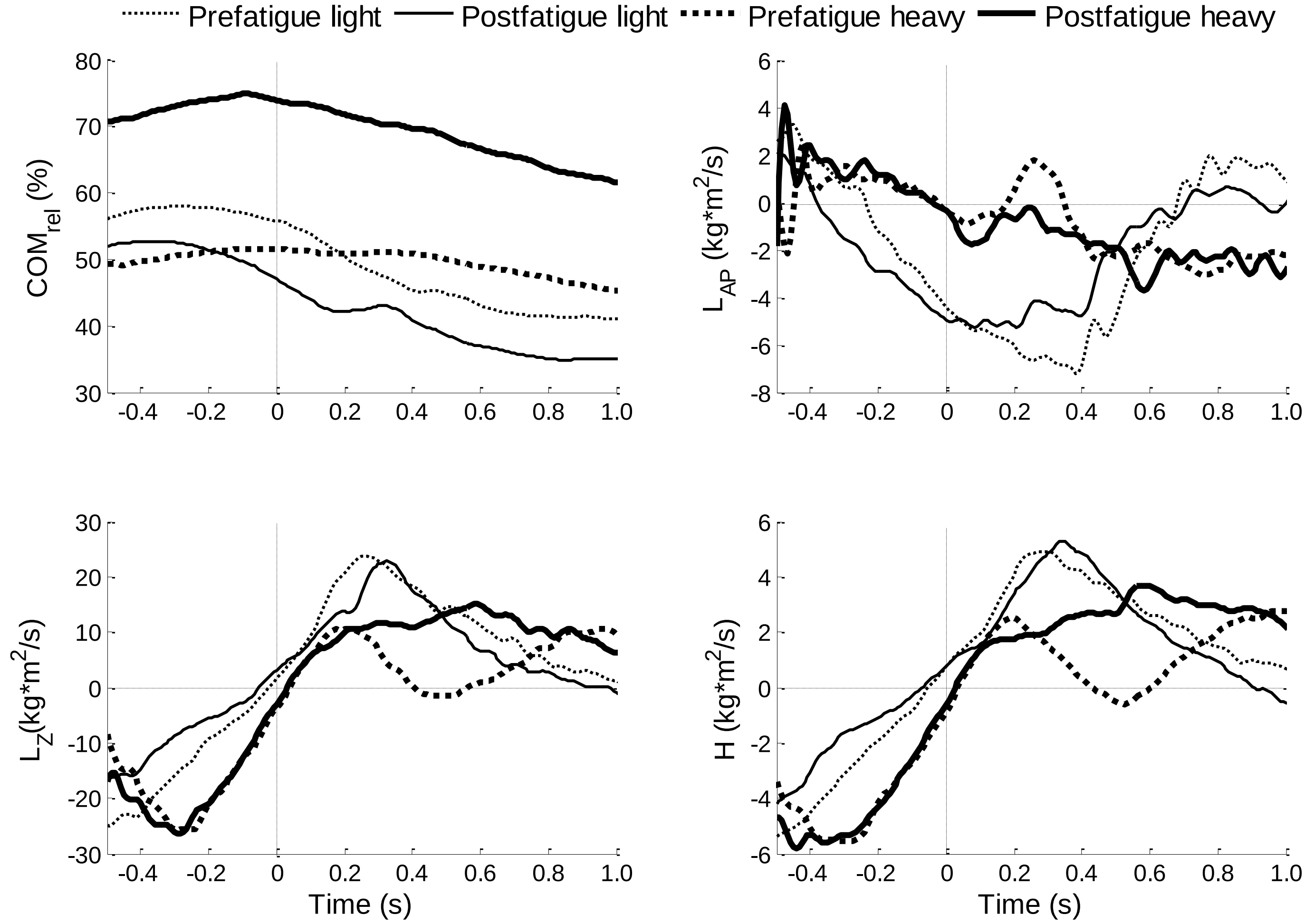

Figure 3.6 Mean post-fatigue responses prior to and following lifting onset, for relative COM location (COM_{rel}), linear momentum in the horizontal direction (L_{AP}), linear momentum in the vertical direction (L_Z), and angular momentum (H) for the post-fatigue conditions. Negative values of L_{AP}, L_Z, and H indicate a backward velocity, a downward velocity, and a forward rotation, respectively.

A significant interaction effect of actual object mass × fatigue was observed on COM_{rel} with a small effect size (Figure 3.7). Fatigue did not have a significant effect for the light load, but post-fatigue values of COM_{rel} were 1.6% larger, (i.e., moved toward the toes). For the heavy group, COM_{rel} moved forward by 13.3% after the fatigue.

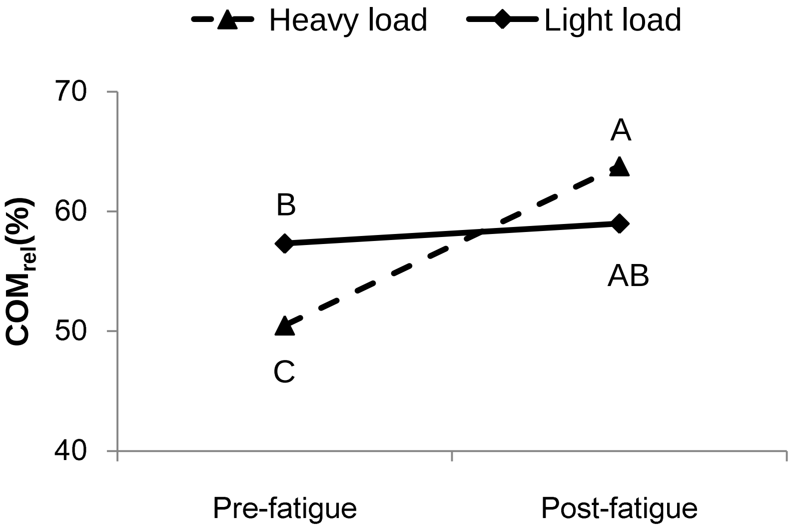

Figure 3.7 Interactive effect of actual object mass and fatigue on the mean relative COM location (COM_{rel}) over the 0.5 s prior to lifting onset. Pairs of values with different letters are significantly different. Errors bars not shown for clarity (SD range = 6.9% ~ 16.0%).

Significant interaction effects of actual object mass × time were found on L_{AP}, L_Z, and H. After ~ -0.4s, the light load led to smaller L_{AP}, and larger L_Z and H. No evident trends were found for these three measures before -0.4s. No significant interaction effects of fatigue × time or the second order interaction effects of actual object mass × fatigue × time were found on all COM-base measures with consistently small effect sizes.

Effects Following Lifting Onset

ANOVA results for COM-based measures obtained after lifting onset are summarized in Table 3.5. A significant difference between the two actual object mass conditions was found on COM_{rel}, with 8.8% smaller values observed with the light load. The corresponding effect size was medium. Fatigue only significantly affected COM_{rel}, which moved forward by 5.5% post-fatigue. Time significantly affected all COM-based measures with corresponding effect sizes ranging medium to large.

Table 3.5 Summary of ANOVA results (p – values) and effect sizes (η^2), for the effects of actual object mass (M), fatigue (F), and time (T) on COM-based measures after movement onset. The symbol * indicates a significant effect ($p < 0.05$).

Measures		Mass (M)	Fatigue (F)	Time (T)	M × F	M × T	F × T	M × F × T
COM_{rel}	p	0.029*	<.0001*	<.0001*	<.0001*	0.74	0.99	0.99
	η^2	0.13	0.034	0.091	0.052	0.009	0.001	0.003
L_{AP}	p	0.062	0.82	<.0001*	0.37	<.0001*	0.89	0.55
	η^2	0.028	0.00	0.095	0.001	0.30	0.008	0.014
L_Z	p	0.075	0.19	<.0001*	0.0004*	<.0001*	0.023*	0.06
	η^2	0.032	0.002	0.216	0.018	0.16	0.018	0.025
H	p	0.15	0.056	<.0001*	0.004*	<.0001*	0.0004*	0.28
	η^2	0.032	0.005	0.154	0.011	0.19	0.043	0.016

Significant interaction effects of actual object mass × fatigue were found on all measures expect for L_{AP}, though with small effect sizes. There were no significant fatigue effects on any of the three measures when the light load was lifted. In contrast, fatigue resulted in larger COM_{rel} , L_Z, and H when lifting the heavy load.

Significant interaction effects of actual object mass × time were found on L_{AP}, L_Z, and H with consistently large effect sizes. Before ~ 0.5s, the light load led to smaller L_{AP}, and larger L_Z and H versus the heavy load, with an opposite trend after 0.5s (Figure 3.6). Significant interaction effects of fatigue × time were found on L_Z, and H with small effect sizes, however no consistent patterns were observed (Figure 3.6). No second order interaction effects of actual object mass × fatigue × time were found.

ANOVA results for COP-based measures are summarized in Table 3.6. A significant main effect of actual object mass was found only on EA, which was 119% larger in the light load condition. The corresponding effect size was also large. Fatigue had no significant main effects or interaction effects with actual object mass on any of the three measures, and had consistently small effect sizes.

Table 3.6 Summary of ANOVA results (*p* – values) and effect sizes (η^2), for the effects of actual object mass (M) and fatigue (F) on COP-based measures after movement onset. The symbol * indicates a significant effect ($p < 0.05$).

Measures		Mass (M)	Fatigue (F)	M ×F
EA	p	0.05*	0.084	0.81
	η^2	0.172	0.036	0.001
MV_{AP}	p	0.075	0.099	0.45
	η^2	0.148	0.031	0.006
MV_{ML}	p	0.88	0.73	0.46
	η^2	0.001	0.002	0.009

3.5 Discussion

The current study aimed to compare the effects of lifting an unexpectedly heavy and light object on postural control and also whether the effects of unexpected load were magnified by localized muscle fatigue of the lumbar extensors. Lifting an unexpectedly heavy and light object was found to compromise postural control. Up to about 0.3s after the onset of load movement, lifting an unexpectedly light object resulted in larger magnitudes of linear and angular momenta than when lifting an expectedly light object. Lifting an unexpectedly heavy object resulted in smaller magnitudes of linear and angular momenta than the expectedly heavy object. These findings suggested that both unexpected conditions resulted in inappropriate preparatory movements. The temporal patterns of linear and angular momenta after the onset of upward movement in the unexpectedly heavy condition also indicated that some participants required a second attempt to complete the lift due to the fail of the initial one, which confirmed the inappropriate preparatory movements. An unexpected change to load mass also resulted in significantly larger COP-based measures after the onset of lifting, which indicated compromised postural control performance. The larger increase in MV_{AP} induced in the unexpected conditions with the light load indicated that lifting an unexpectedly light object had more substantial effects on postural control than lifting an unexpectedly heavy one. Lumbar extensor fatigue was expected to further compromise postural control while lifting an object with unexpected mass. However, the current findings did not provide supporting evidence. Fatigue did not result in evident differences in the temporal patterns of COM-based measures, except for an additional forward movement of COM_{rel} prior to the onset of lifting an unexpectedly light object. No fatigue-related effects were observed on COP-based measures.

As noted, lifting either an unexpectedly heavy and light object led to compromised postural control, as indicated by increased postural sway measures obtained after the onset of lifting. Furthermore, the differences in linear and angular momenta found between unexpected and expected conditions indicated that lifting an unexpected mass resulted in an incorrect preparation to counteract disturbing effects. If so, this could impose a further increased threat to postural control, as suggested by Commissaris and Toussaint (1997), and van der Burg et al. (2000). For the light load, the unexpected condition resulted in larger magnitudes of linear and angular momenta. Specific values suggest that participants moved much faster backward and upward than intended, since they were programmed to counteract the disturbing effects of lifting a heavy object which was too much for lifting a light object. For the heavy load, the unexpected condition resulted in smaller magnitudes of momenta, suggesting that preparatory movements were not sufficient to counteract the disturbing effect of lifting a heavy object; instead, these movements were programmed for a light object. As a whole, these findings are consistent with previous studies (Commissaris and Toussaint, 1997; van der Burg et al. 2000).

The more profound effect of lifting an unexpectedly light vs. heavy object on postural control also is in accordance with existing evidence. Commissaris and Toussaint (1997) reported that overestimation of a load during lifting caused a disturbance of balance in 92% trials, which was not found in another study that investigated the effects of underestimation of a lifted load (van der Burg et al., 2000). The exact underlying mechanisms responsible for such difference between load masses are unclear. One potential explanation could be the different mechanical loads placed on the lumbar spine in the two unexpected conditions. An increased mechanical load was reported in situations involving overestimation of object mass, while a decreased mechanical load was found in conditions of underestimation (Commissaris and Toussaint, 1997; van der Burg et al. 2000). Further, Lee et al. (2008) indicated a degradation of trunk postural control as trunk exertion force increased. Thus, the larger mechanical load placed on the lumbar spine by lifting an unexpectedly light object may result in more degradation to trunk postural control, leading to larger impairments to overall postural control

The temporal patterns in COM-based measures after the onset of upward lifting were consistent with those of Commissaris and Toussaint (1997) and van der Burg et al. (2000). However, prior to the onset of lifting, differences were evident in COM_{rel} and L_{AP} between the expected and unexpected conditions (Figure 3.2); these differences are contradictory to the earlier work noted, neither of which reported any differences prior to lifting. This discrepancy is likely due to the different methods used to determine the onset of lifting. Both earlier studies determined onset based on the position of markers attached to the box (vs. use of a force platform here). Another contributing factor is likely to be differences in lifting techniques. Here, participants were instructed to employ a stoop lifting technique, while in the earlier studies no specific instructions were given. Furthermore, Commissari and Toussaint (1997) compared the unexpectedly light condition with the expectedly heavy condition. In the current study, differences between those two conditions were less evident than between the expected and unexpected conditions for both loads.

Fatigue was expected to interact with lifting unexpected loads to result in more substantial adverse effects on postural control. However, the current results did not provide clear supporting evidence. The specific fatiguing protocol may have induced insufficient decrements in postural control (as discussed in Chapter 2), and hence the experiment may have been insufficiently sensitive to detect the effects anticipated. Mean post-fatigue decreases in strength (MVIC) were only 31.7% (22.1%), less than the intended level (60%), and perhaps not high enough to lead to observable influences. However, the current findings may also just suggest that lumbar muscle fatigue did not impose greater postural threat when lifting an unexpected mass object. A similar lack of fatigue-related effects was also reported by Chow et al. (2004), who investigated the effect of fatigue on the muscular and postural response to sudden release of lifting loads. Their results indicated that postural stability after sudden release of a load during stoop lifting was actually greater (less COP excursion) when lumbar extensor fatigue was present. In the current study, though failing to reach statistical significance, lumbar muscle fatigue did result in smaller EA and MV of COP. Chow et al. (2004) suggested that the improved postural control could be attributed to the reduced strength of the lumbar extensors following fatigue: the reduced strength may imply that the lifting force, and therefore the perturbation following unexpected load, was lower in a fatigued condition. Our data support this interpretation, given the lower values of L_Z and H observed during the first 0.3 s following the onset of lifting in the fatigued conditions. However, further work is needed to confirm the exact contributing factors.

One methodological issue warrants discussion here. Since each participant was exposed twice to an unexpected load, a learning effect may be present during the second exposure. Furthermore, although participants did not know when the mass of lifting object would change, they did know that they would lift objects with different mass, which was stated in the informed consent form. Thus, the current results may not reflect a truly unexpected condition, as the participants would have been anticipating the object mass change to some extent. Although the overall reported level of expectation was quite low, and there was not a significant difference in the level of expectation between the pre- and post-fatigue conditions, a slight increase (3.9 to 8.4) was observed in the latter. Furthermore, the pre-fatigue failures in lifting the heavy box that were observed immediately after lifting onset in the unexpected condition (Figure 3.6) were not observed after the fatigue, which also suggests an increased level of expectation.

Another potential concern is a gender difference in fatigability of the lumbar extensors (Larivière et al., 2006). To address this issue, unpaired *t*-tests were performed on ΔMVIC and exercise duration to assess gender differences related to the fatiguing exercises. Both strength decreases and exercise duration were comparable between the two genders ($p > 0.66$). Mean decreases in muscle strength were 34.3% and 29.2% for males and females, respectively, with corresponding exercises durations of 7.9 and 8.1 min. Additional analyses were performed by including gender in the ANOVAs used to assess the effects of actual object mass, expectation, and fatigue on each of the dependent measures. No gender-related effects were observed on any COP-based measures ($p > 0.06$). Several significant interaction effects with gender were evident on COM-based measures. However, qualitatively, the main and interactive effects of the primary independent variable were quite similar for both genders.

Several potential limitations should be noted in the proposed study. First, individual variability between two lifting load s may be a concern, since both anthropometry and stance can influence COP-based measures (Chiari et al., 2002; Day et al., 1993; Kirby et al., 1987). However, no significant differences in age, body mass, or stature were observed between groups. Lifting stance may have differed between the two groups, since it was not tightly controlled (and was not measured). Second, generalization of the current findings requires some cautions. A fair level of control was exerted over many sources of variability, such as the load and lift technique, factors which have been demonstrated to influence postural control (as summarized in Introduction section). Future studies should be conducted to determine whether comparable effects would be present for other lifting conditions and which lifting technique would be better at mediating the effects of unexpected load in terms of postural control. Muscle fatigue was induced by tightly controlled exercise and only induced at lumbar extensors, and future work is needed to determine the effects of fatigue at other muscle groups and in more realistic fatiguing activities. Finally, generalization to other populations is unknown (individuals differing in age, presence of pathologies, etc.).

The results of this study have several practical implications. Consistent with earlier work, an incorrect estimation of the mass of an object to be lifted clearly compromised postural control and led to an increased falling risk. The differential effects of two unexpected conditions suggested that lifting an unexpectedly light object may lead to a higher falling risk than an unexpectedly heavy object. Such information can be used in education and safety training, for example by emphasizing the possibility of injury resulting from incorrect load estimation during lifting. There may also be benefit in training workers to perform adequate preparations in situations where only visual information of loads is available. Lumbar extensor fatigue did not further compromise postural control during lifting an unexpected load, suggesting that muscle fatigue, at least at the location and level investigated here, may not be a major contributing risk factor during MMH tasks.

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Chapter 4: Efficacy of three interventions at mitigating the adverse effects of muscle fatigue on postural control

4.1 Abstract

This study evaluated the efficacy of three interventions aimed at mitigating the adverse effects of muscle fatigue on postural control. The first intervention provided periodic rest breaks scheduled according to subjective perceptions of decrements in postural stability, while the other two involved auditory stimulations (static pure tone and moving conversation). A group of 16 young healthy participants performed repetitive box handling (lifting + lowering) over 1.5 hours to induce muscle fatigue. Trials of quiet upright stance were completed at 10- minute intervals, during which the interventions (or a control condition) were applied. During these trials, postural control was assessed using perceived stability (PS) and several measures derived from center-of-pressure (COP) time series: mean velocity (MV), sway area (SA), and detrended fluctuation analysis (DFA) exponent. Allowance of rest breaks did not significantly affect any of the objective measures, though there was a trend indicated an offset in fatigue-induced decreases in PS. Compared to the control condition, both the static pure tone and moving conversation led to significant changes in the dependent measures that indicated a mitigation of fatigue-induced postural instability. These results may facilitate the development of strategies to prevent occupational falls related to muscle fatigue.

Keyword: postural control, muscle fatigue, intervention, auditory stimulation, falls

4.2 Introduction

Falls continue to be an important occupational safety concern. Although the total number of occupational fatalities decreased slightly from 2005 to 2006, fatal falls increased from 770 to 809, and remained the second most frequent fatal events (BLS, 2007a). For nonfatal cases involving days away from work, falls were the third most common cause, accounting for 234,450 (20%) of 1,183,500 injuries and illnesses in 2006 (BLS, 2007b). Generally, two forms of control measures are used to reduce the risk of fall-related injuries: fall protection and prevention (Hsiao and Simeonov, 2001). Fall protection aims to protect fallers by minimizing injury severity after the initiation of a fall, whereas fall prevention seeks to avoid the initiation of a fall. Current measures, such as implementation of safety regulations and safety equipment, focus more on fall protection rather than prevention (Hsiao and Simeonov, 2001). However, due to lack of use or incorrect use, fall protection is not likely to be completely effective at reducing fall injuries. NIOSH (2000) reported that more than two-thirds of falls from elevation occurred while fall protection devices remained unused or used incorrectly. Thus, there remains a need for fall prevention research, including identifying and understanding the underlying causal factors and finding effective ergonomic interventions to prevent falls.

Primary causes of falls are thought to be slips, trips, and imbalance episodes, which can be considered collectively as loss of balance incidents (Hsiao and Simeonov, 2001). Balance is maintained through postural control, which is a complex motor skill/process involving multiple sensory systems (visual, vestibular, and proprioceptive/somatosensory), motor control, and central nervous system (CNS) integration (Horak, 2006; Punakallio, 2005; Riley et al., 1998; Umphred, 2001). Impaired postural control has been shown repeatedly to be associated with an increased falling risk (Baloh et al. 1995; Fernie et al. 1982; Lichtenstein et al. 1988; Maki et al.

1990; Prieto et al. 1996) and predictive of future falls among older individuals (Bergland and Wyller 2004; Stel et al. 2003; Pajala et al. 2008). A number of risk factors that may compromise postural control have been identified and categorized as environmental factors, task-related factors, and personal factors (Hsiao and Simeonov, 2001). Among them, muscle fatigue is a primary focus of the current work, as it is one important task-related factor that has been linked to a decrement in postural control and a potential increased risk of falling. Thus, strategies that can improve postural control in the presence of muscle fatigue have the potential to reduce falling risks and prevent falls.

Several interventions to improve postural control have been proposed and investigated in the literature. These interventions include tactile feedback, noise input, use of a visual reference, and galvanic vestibular stimulation (GVS). It has been demonstrated that tactile feedback to a diversity of body regions (index fingertip, head, and neck) had the same or more stabilizing effects on postural control compared to force contact (physical support) and three sensory inputs (Jeka et al., 1994; Krishnamoorthy et al., 2002; Lackner et al., 1999; Rogers et al., 2001). Several studies (Gravelle et al., 2002; Priplata et al., 2002 and 2006) reported that noise input (application of subsensory mechanical or electrical noise) to the feet or knee could improve postural control performance for different participant groups (healthy young and older, and individuals with diabetic neuropathy or prior strokes). Simeonov et al. (2003 and 2009) found that providing vertical visual references at different proximal locations could reduce the instability related to elevation and inclination and could improve postural control on deformable surface. GVS is the application of a small amplitude electrical current (less than 4 mA) transcutaneously to the vestibular afferents through electrodes placed over the mastoid bones. GVS can impact postural control by modulating the continuous firing level of the peripheral vestibular afferents (Pavlik et al., 1999). Scinicariello et al. (2001) reported that mechanically-perturbed subjects maintained a more erect stance and followed the movements of the perturbing platform more closely with the application of an appropriate galvanic stimulus.

Despite the potential of each of these methods as interventions, it is difficult to apply light touch stimulus, noise input, or GVS in real occupational settings. Application of a visual reference is also limited to some occupational settings. Hence, simple and effective interventions that can be feasibly applied to occupational settings are still needed for fall prevention.

Previous work has indicated that perceived postural stability can reflect the status or quality of human postural control. Schieppati et al. (1999) investigated the relationships between subjective ratings of body sway and several objective sway measures, and found consistent correlations between the subjective and objective measures for diverse participant groups (normal, neuropathic, and Parkinsonian) and different visual conditions. Adkin et al. (2002) reported that perceived stability was sensitive to changes in postural threat, which was induced by standing at elevation either close to or away from an edge. Additional work has shown that perceived stability reflects changes in objective postural sway measures caused by stance and visual conditions (DiDomenico and Nussbaum, 2005), and is sensitive to improvements in postural control induced by tactile feedback (Tremlay et al., 2004). Based on this evidence, we expected that decrements in postural stability induced by muscle fatigue would be subjectively perceived. Rest breaks scheduled according to perceived decrements in postural stability should allow recovery from fatigue, and hence improve postural control.

One property of human auditory perception is the ability of locate a sound spatially source using both binaural and non-binaural cues. Binaural cues allow localization of the sound in the horizontal plane by using differences in the temporal and intensity characteristics of the sound. Sounds in the median sagittal plane rely on non-binaural cues (Raper and Soames, 1991; Tanaka et al., 2001). Thus, auditory information may facilitate spatial orientation, which is a critical component of postural control (Horak, 2006). Control of balance is maintained through integration of inputs from the visual, proprioceptive, and vestibular systems by the central nervous system (Brocklehurst et al., 1982; Winter, 1995). Given the fact that the vestibular system and cochlea are closely interrelated as fluidic systems, it can be assumed that auditory stimulation can affect postural control.

Several studies have indeed shown that auditory stimulations can impact postural control during static stance, although these findings are not consistent and the effects may depend on the type of auditory stimulation. Njiokiktjien (1973) found that healthy individuals showed a substantial reduction in postural sway when they performed an auditory task. Era and Heikkinen (1985) reported that individuals exposed to noise at work had poorer postural control, indicated by greater postural sway magnitudes, than those without such exposure. Raper and Soames (1991) investigated the influence of stationary auditory fields (pure tone and general background conversation) with sound sources from four directions on postural sway, and suggested that stationary auditory stimulations generally had adverse effects on postural sway. Similar destabilizing effects of moving auditory fields have also been demonstrated by Soames and Raper (1992). Sakellari and Soames (1996) evaluated the effects of sound loudness and frequency on postural sway and suggested that sound stimuli in an appropriate frequency range could suppress postural sway. Easton et al. (1998) evaluated the effects of stationary auditory stimulation in sighted and blind individuals and found that symmetric bilateral auditory stimulation reduced postural sway in a tandem Romberg stance for both groups. Tanaka et al. (2001) reported that a laterally moving auditory stimulation led to higher lateral sway in an older group versus a younger group. Given this existing evidence, two types of auditory stimulations (static vs. dynamic) were selected and examined in the current study.

Overall, the aim of this study was to evaluate the efficacy of three interventions (periodic rest breaks scheduled based on perceived stability, static pure tone, and moving conversation) at mitigating the adverse effects of muscle fatigue on postural control. It was hypothesized that: 1) postural control during quiet upright standing would be improved by providing periodic rest breaks during the fatiguing work, and 2) the static pure tone would improve postural control and would have a more substantial effect in the lateral (ML) vs. sagittal (AP) direction, 3) moving conversation would compromise postural control during the fatiguing work. Results from this work were intended to facilitate the development of strategies to prevent occupational falls related to muscle fatigue.

4.3 Methods

4.3.1 Overview of Experimental Design

A repeated measures design was used, in which each participant completed four experimental sessions involving a repetitive, fatiguing lifting task and measures of task-induced changes in postural control, perceived stability, and fatigue. Each session involved one of three “interventions” (static pure tone, moving conversation, and rest breaks), as described below, along with a control condition. Sessions were separated by a minimum of two days to avoid residual effects of fatigue, and the order of the conditions was counterbalanced using Latin squares. Participants also completed an initial practice and familiarization session.

4.3.2 Participants

Sixteen young healthy participants (18-24 years old, 8 males and 8 females) from the university and local community volunteered for this study (Table 4.1). This age group was intended to represent individuals near the typical beginning of working life, and to control for potential age-related effects. Participation was limited to those who reported moderate levels of regular physical activity, no current injuries, musculoskeletal disorders, neurological disorders, or vestibular disease, no occurrences of falls in the past 12 months, and no auditory diseases or any conditions that could affect their hearing. All completed an informed consent procedure approved by the University Institutional Review Board.

Table 4.1 Participant characteristics [mean (sd)]

	Age (years)	Stature (cm)	Body Mass (kg)
Male	20.3 (1.4)	180.7 (11.3)	79.5 (15.1)
Female	21.3 (1.6)	164.9 (4.3)	62.8 (5.9)

4.3.3 Pre-fatigue Measures

Pre-fatigue measures were obtained of resting heart rate (HR), ratings of perceived discomfort (RPD) and stability, postural control, and lumbar extension strength. Resting HR (bpm) was obtained using a heart rate monitor (Polar S810, Lake Success, NY, USA), as the average value during the last 3 min during a 5 min resting period at the beginning of each experimental session. RPDs localized to the lumbar extensors were provided using the Borg-CR10 scale (Borg, 1982), which was modified to assess discomfort rather than exertion as developed originally. Initial practice with (calibration to) the Borg-CR 10 scale was provided, by having participants perform a wall-squat task during the practice session.

Three pre-fatigue trials of quiet standing were obtained, with a rest period of one minute between each. Use of three replications was intended to improve reliability over a single observation (Lafond et al. 2004). Standing trials lasted 75 sec, during which participants stood on a force platform (AMTI OR6-7-1000, Watertown, MA, USA), with their arms at their sides, feet together, head pointed straight ahead, and eyes closed. Repeatability of foot placement between trials was maintained by outlining the feet on poster board placed on top of the force platform. Each participant wore the same shoes across four experimental sessions. Triaxial ground reaction forces and moments were sampled at 120 Hz.

Participants were instructed to "concentrate on standing as still as possible" and to think about their level of “perceived stability” during the period of the quiet standing. Ratings of perceived stability (PS) were provided using a visual analog scale and procedures adapted from those described by Schieppati et al. (1999). Participants were initially “calibrated" to the two extremes of the scale. For the lower extreme (0), they adopted a unilateral stance with eyes closed. For the upper extreme (100), they stood with eyes open while holding a rigid object.

Strength of the lumbar extensors was assessed using maximum voluntary isometric contractions (MVICs). These were conducted from a 20 °forward-flexion posture, while participants stood on a force platform (Bertec 4550-08, Worthington, OH, USA) and pushed backward against a fixed, padded frame at the level of the scapulae. A customized frame was attached to the force platform to partially isolate the lumbar extensors. Initial warm-up exercises were completed, consisting of 20 lifts of a box weighing 10% of individual body weight. During MVICs, participants were instructed to perform the back extensions “as hard as possible” for 5 s and were given non-threatening verbal encouragement. At least five MVICs were performed, with one-minute of rest between each. If an increasing trend in peak torque was evident at the fifth MVIC, additional replications were performed until performance stabilized. The largest extensor torque was designated as the pre-fatigue MVIC for each participant.

4.3.4 Fatiguing Task

Fatigue was induced through repetitive box handling (lifting + lowering) over 1.5 hours. The initial 30-minute was designed as a warm-up phase, with the remaining 1-hour intended as the fatiguing phase. During the warm-up phase, the weight of the box was increased gradually, from 10-25% of the participant’s body weight (BW) as follows: 10% of BW from 0-5 min, 15% of BW from 5-10 min, 20% of BW from 10-20 min, and 25% of BW from 20-30 min. During the fatiguing phase, the weight was maintained at 25% of BW. The specific weights and time periods were determined during pilot work as moderately fatiguing for most individuals. In both phases, participants repetitively lifted and lowered the box between a shelf set at knee height and knuckle height. Lifting frequency was set at 12 lifts + lower cycles per minute, a rate similar to that used in several prior studies (Garg et al., 1979; Marras et al., 2006; Shu et al., 2005; Yang et al., 2007), and was controlled by an acoustic metronome. Participants were instructed to perform the lifts symmetrically in the sagittal plane, to use their back muscles primarily, and to use a consistent lifting style. The position of the feet relative to the box and stance width were self-selected by participants.

During the lifting phase, HR and RPD were obtained after each 10-minute period. A single quiet standing trial was also performed after each 10-minute period, using the procedures described above. Upon completion of the fatiguing phase, a single post-fatigue MVIC of the lumbar extensors was completed.

4.3.5 Interventions

Periodic rest breaks

Rest breaks were inserted during the lifting task according to subjective decrements in perceived postural stability (PS). Recall that PS was obtained after each 10-minute period during the fatigue phase. If a PS score decreased more than 15% from the mean of pre-fatigue values, then participants were provided a 5-minute, seated rest break. After the break, one quiet standing trial was performed and another PS was obtained. If PS remained more than 10% below the pre-fatigue level, another 5-minute break was provided. This process was repeated until the decrease in PS was less than 10%, at which time participants re-started the fatiguing lifting task. Rest break durations were monitored, and the duration of the fatigue phase was extended, as necessary, to maintain the duration of box handling at 1-hr. However, HR and RPD were still obtained at the end of each 10-minute box handling period and were followed by one quiet standing trial.

Auditory stimulations

The second and third interventions were two types of auditory stimulations presented during the quiet standing trials. The first auditory stimulation involved presenting a static pure tone with a frequency of 1500 Hz, which was selected based on the existing evidence that the sound with a bandwidth from 1480 to 1720 Hz has the greatest stabilizing effect on postural control (Sakellari and Soames, 1996). Signal intensity was 60 dB at the ear, similar to normal conversation at 1 m

(Berger et al., 2000). The static pure tone was presented using two speakers (Harman Kardon 06941V, Northridge, CA, USA) placed 1 m to the right and left sides of participants at head height. The second auditory stimulation was intended to mimic general conversation, with the source moving relative to an individual. Recorded conversation was presented using four speakers placed 1 m to the front, rear, right, and left sides of participants at head height. The auditory source was moved among the four speakers randomly, changing at a frequency of 0.2 Hz and with a fixed intensity of 60 dB at the ear. In both interventions, the auditory signals were controlled using Adobe Audition 3.0 (Adobe Systems Inc., San Jose, CA, USA). Note that, in contrast to the static pure tone, moving conversation was expected to lead to postural instability, and hence the "intervention" being assessed was removal of such auditory input.

4.3.6 Data Processing and Dependent Measures

HR, RPD, and MVIC were used to derive measures of fatigue induced by the repetitive lifting task. Average HR was determined during the final two minutes of each 10-minute box handling period, then normalized to each participant's measured resting HR and age-predicted maximum HR (Eastman Kodak Company, 2004), and expressed as %HR. Increases in HR were considered indicative of general physical fatigue (Astrand, 1960; Gamberale, 1972; Kilborn, 1971; Lotz, et al., 2007). Increases in RPD (ΔRPD = post-fatigue - pre-fatigue) served as an additional measure of fatigue (Barnekow-Bergkvist et al., 2004; Lotz, et al., 2007; Oberg et al., 1994; Soh et al., 1996). A final measure was obtained from the percent change in MVIC [ΔMVIC = (pre - post)/pre], as in earlier studies (Joborn et al., 1988; Yassierli et al., 2007).

Postural control was assessed using PS and measures derived from the forces platform during quiet standing. Force platform data were low-pass filtered (2nd order, zero-phase-lag, Butterworth, 5 Hz cut-off frequency), and transformed to obtain center-of-pressure (COP) time series (Winter, 2004). The initial 10 s and last 5 s of data were removed, yielding a sampling duration of 60 s; this duration was considered adequate for stability and reliability of summary COP measures (Carpenter et al., 2001). COP-based measures used here are the same as in Chapter 2. Briefly, from each COP time series mean velocity (MV), sway area (SA), and DFA exponent were determined. Mean velocity and DFA exponent were determined in both the antero-posterior (AP) and medio-lateral (ML) directions.

4.3.7 Statistical Analyses

Preliminary analyses were conducted to investigate if participants were fatigued to a similar level in the four sessions. One-way repeated-measures analyses of variance (RANOVAs) were performed on pre-fatigue HR, RPD, and MVIC, as well as ΔMVIC, to identify effects of condition (control, static pure tone, moving conversation, and rest breaks). Two-way RANOVAs were performed on ΔRPD and %HR to assess the main and interactive effects of condition and time (i.e. samples obtained after each 10-min period of box handling). The order of exposure to conditions served as a blocking variable in these RANOVAs. Where relevant, *post hoc* comparisons were conducted using Tukey's Honestly Significant Difference (HSD) tests.

In the control condition, effects of the fatiguing lifting task on postural control measures were determined using one-way RANOVAs, with the independent variable of time. MV_{ML}, MV_{AP}, and SA were log-transformed to achieve normally distributed residuals, though summary statistics are given in the original units. A significant main effect of time was followed with two-sample *t*-tests to determine at which times post-fatigue values were significantly different from pre-fatigue values.

To identify if there were significant differences in pre-fatigue postural control measures in the four conditions, two-way (condition and replication) RANOVAs were performed, with the order of exposure to conditions as a blocking variable. MV_{ML}, MV_{AP}, and SA were log-transformed to achieve normally distributed residuals. Significant main effects of condition were observed on DFA_{ML} ($p = 0.003$) and PS ($p = 0.008$). Given this, PS and each of the COP-based dependent measures were converted to proportional differences ($\Delta = (\text{post} - \text{pre})/\text{pre}$) and the following analyses were performed on these differences.

In the rest breaks condition, only eight participants exceeded the PS criterion and thereby received rest breaks. Thus, participants were divided into two subgroups (no break vs. break) and the effects of rest breaks were analyzed separately from the other interventions. Two-way mixed-factor ANOVAs were performed with condition (control vs. rest breaks) as a within-subject variable and subgroup (no break vs. break) as a between-subject variable, on measures obtained in the last trial of the lifting phase. The order of exposure to conditions served as a blocking variable. Here, and in subsequent analyses, effect sizes (η^2) of the main and interactive effects were calculated from the estimated variance components and were interpreted using the following criteria: ~0.01 small, ~0.06 medium, and ~0.14 large (Cohen, 1988).

To investigate the effects of the two auditory stimulations, two-way RANOVAs were performed with independent variables of condition (control, static pure tone, and moving conversation) and time, with order of exposure to conditions as a blocking variable. Since time was a repeated measures factor, and presentation order of the levels was neither randomized nor counterbalanced, Mauchly's tests were performed on all dependent measures to assess the sphericity assumption. Significant violations were found on MV_{ML} and PS ($p < 0.005$). Thus, multivariate tests were performed on these two measures. However, the results of multivariate tests were essentially the same as the univariate tests. Thus, only the results of univariate tests are presented for simplicity and due to the relatively small sample size (Tabachnick and Fidell, 2007). Where relevant, HSD tests were used for *post hoc* comparisons. The level of significance for all statistical tests was set at $p < 0.05$, and all statistical analyses were performed using JMP 8.0 (SAS Inc., Cary, NC, USA). Summary results are presented as means (SD).

4.4 Results

4.4.1 Fatigue Extent

No significant condition effects were found on pre-fatigue MVIC, RPD, HR, or ΔMVIC ($p > 0.47$) with effect sizes ranging from 0 to 0.02. Across all conditions, ΔMVIC was 24.5% (13.7%). There were significant main effects of condition ($p < 0.0001$) and time ($p < 0.0001$) on ΔRPD, with effect sizes of 0.02 and 0.11, respectively. The largest increase in RPD was observed in the control condition (4.2 (2.2)) and the smallest in the static pure tone condition (3.3 (2.1)). RPD increased progressively over the 60 min of the fatigue phase (Figure 4.1), with no evident differences in this pattern between conditions ($p = 0.99$, $\eta^2 = 0.003$). Mean %HR was 21.4% (5.4%), and no main or interaction effects of condition or time were observed ($p > 0.22$, $\eta^2 = 0.004 \sim 0.006$).

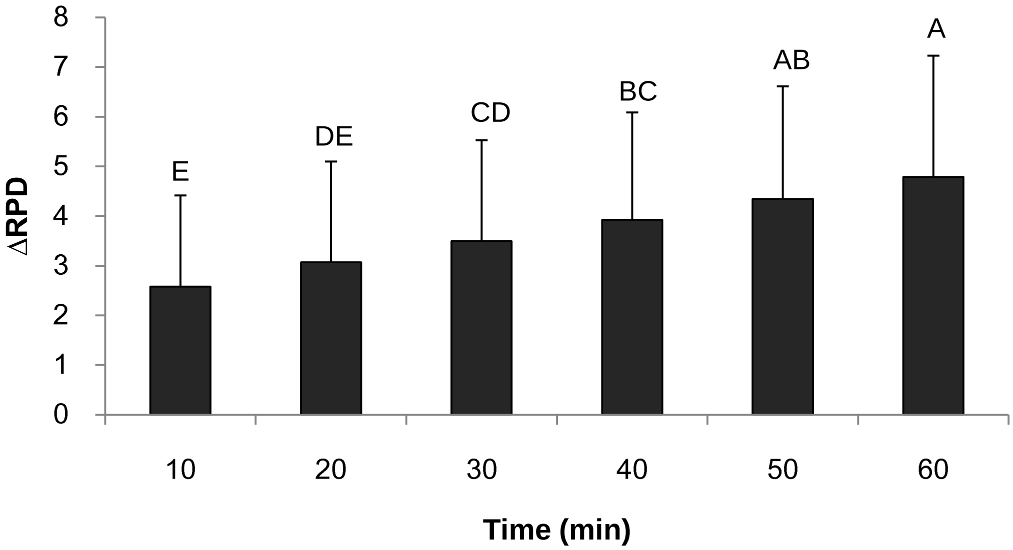

Figure 4.1 Changes in ratings of perceived discomfort (RPD) after each 10 min lifting period during the fatigue phase; values are changes in RPD (ΔRPD) relative to pre-fatigue measures. Pairs of values with different letters are significantly different, and errors bars indicate standard deviations.

4.4.2 Effects of Fatiguing Lifting Task on Postural Control

Significant time effects were found on MV_{AP}, SA, DFA_{AP}, and PS ($p < 0.02$, $\eta^2 = 0.02 \sim 0.09$). The fatiguing lifting task resulted in significantly larger MV_{AP}, SA, and DFA_{AP}, and smaller PS at nearly all of the measurement times (Figure 4.2). SA and PS exhibited progressive increases and decreases, respectively, over the 1-hr of repetitive lifting. Such trends were not evident with MV_{AP} and DFA_{AP}. A borderline effect of time was found on MV_{ML} ($p = 0.06$, $\eta^2 = 0.02$), and there was no effect on DFA_{ML} ($p = 0.73$, $\eta^2 = 0.01$).

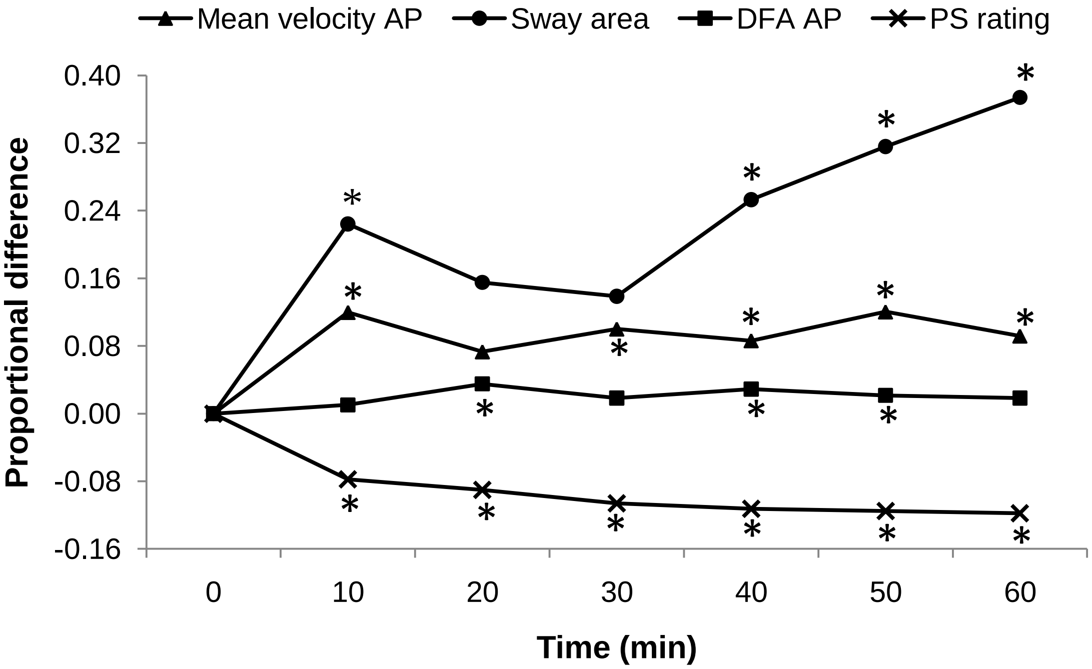

Figure 4.2 Effects of the fatiguing lifting task on several measures of postural control. Values are proportional differences, and the symbol * indicates a significant difference from the baseline value ($p < 0.05$). Errors bars not shown for clarity (SD range = 0.03 ~ 0.60).

4.4.3 Intervention Effects

Effects of Rest Breaks

Summary results for the control and rest break conditions are presented in Table 4.2. Allowance of rest breaks did not affect any of the objective measures ($p > 0.16$, $\eta^2 = 0.016 \sim 0.057$), though this effect was borderline on PS ($p = 0.063$, $\eta^2 = 0.087$). Differences between the breaks and no breaks subgroups were not significant ($p > 0.09$, $\eta^2 = 0 \sim 0.12$), and the condition × subgroup interaction was also non-significant ($p > 0.08$, $\eta^2 = 0.002 \sim 0.088$). The break subgroup, however, showed smaller increases in MV and less decreases in PS when breaks were allowed versus the control condition.

Table 4.2 Proportional differences in postural control measures for the two subgroups in the control and rest breaks conditions. Results are given as means (SD).

Group	Condition	MV_{ML}	MV_{AP}	SA	DFA_{ML}	DFA_{AP}	PS
No break	Control	0.153 (0.333)	0.098 (0.191)	0.561 (0.616)	0.002 (0.048)	0.030 (0.034)	-0.067 (0.126)
	Rest breaks	0.041 (0.205)	-0.058 (0.170)	-0.085 (0.565)	-0.029 (0.054)	0.019 (0.043)	-0.029 (0.223)
Break	Control	0.146 (0.361)	0.085 (0.170)	0.187 (0.565)	-0.027 (0.054)	0.007 (0.043)	-0.169 (0.223)
	Rest breaks	0.102 (0.239)	0.055 (0.200)	0.222 (0.781)	-0.032 (0.063)	0.001 (0.037)	-0.046 (0.068)

Effects of Auditory Stimulations

Significant main effects of condition were observed on all dependent variables except for MV_{ML} and PS, with corresponding effect sizes that were small to medium (Table 4.3). The control condition resulted in the largest increases in MV_{AP}, SA, and DFA_{AP}, and the smallest decreases in DFA_{ML} (Figure 4.3). Moving conversation showed significantly smaller increases in MV_{AP} compared to the static pure tone. Otherwise, no significant differences in postural control measures were observed between the two auditory stimulations. No main or interactive effects of time were found, and the corresponding effect sizes were consistently small.

Table 4.3 Summary of ANOVA results (p–values and effect sizes (η^2)), for the effects of condition (control, static pure tone, and moving conversation) and time on several measures of postural control. The symbol * indicates a significant effect ($p < 0.05$).

Measures		Condition (C)	Time (T)	C × T
MV_{ML}	p	0.055	0.37	0.97
	η^2	0.013	0.012	0.008
MV_{AP}	p	<.0001*	0.66	0.89
	η^2	0.063	0.007	0.011
SA	p	0.0002*	0.12	0.95
	η^2	0.045	0.022	0.01
DFA_{ML}	p	<.0001*	0.20	0.99
	η^2	0.07	0.019	0.002
DFA_{AP}	p	0.015*	0.66	0.69
	η^2	0.019	0.007	0.017
PS	p	0.12	0.64	0.98
	η^2	0.008	0.007	0.006

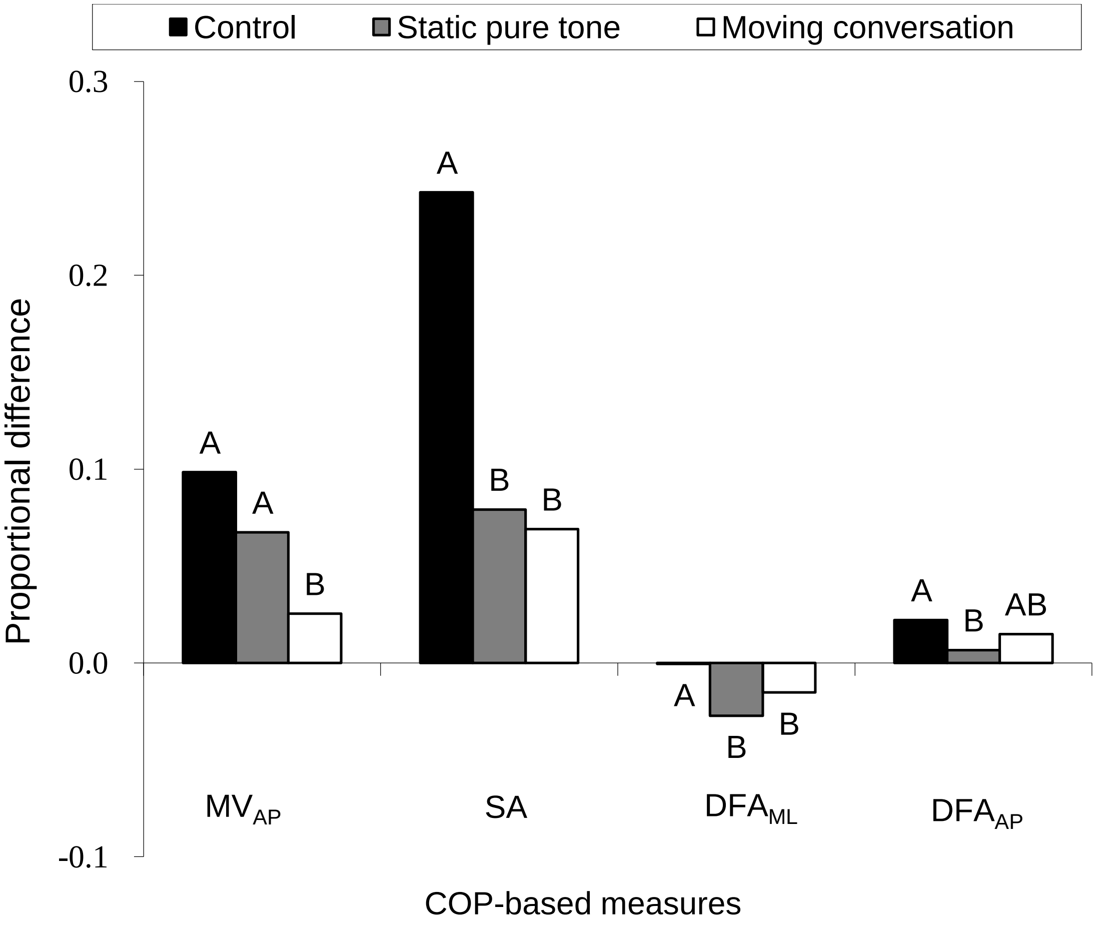

Figure 4.3 Effects of static pure tone and moving conversation on several measures of postural control. Values are proportional differences, and pairs of values with different letters are significantly different ($p < 0.05$). Errors bars not shown for clarity (SD range = 0.036 ~ 0.450).

4.5 Discussion

The current study aimed to evaluate the efficacy of three interventions at mitigating the adverse effects of localized fatigue on postural control. Periodic rest breaks, overall, resulted in no significant differences relative to the control condition. Application of a static pure tone during quiet standing resulted in significantly smaller fatigue-induced increases in SA and DFA_{AP}, and larger decreases in DFA_{ML} compared to the control condition. Moving conversation led to significantly smaller post-fatigue increases in MV_{AP} and SA, and larger decreases in DFA_{ML} than the control condition. There was no significant difference between the two auditory inputs, except for a smaller increase in MV_{AP} for moving conversation.

4.5.1 Effects of Rest Breaks

Periodic rest breaks were expected to improve postural control, and offset the adverse effects of fatigue induced by the repetitive lifting/lower tasks. However, no significant difference was observed between the rest breaks and control conditions for the break subgroup. Smaller increases in MV and smaller decreases in PS were observed for the break subgroup when breaks were allowed versus the control condition. However, a similar trend was more evident for the no break subgroup. Though failing to reach significance, the no break subgroup showed improvement in all dependent measures in the rest breaks condition. Though the specific reasons are unclear, a learning effect may account for such improvement, since significant order effects were found on MV_{ML} ($p = 0.01$) and SA ($p = 0.03$). As well, there were significant order effects on two fatigue measures: RPD differences ($p < 0.001$) and %HR ($p = 0.0006$).

It is difficult to explain the lack of beneficial effects of rest breaks on postural control. One possibility is that the decrement in postural control induced by the current fatiguing task was not large enough for participants to perceive; specifically, the decrease in lumbar extensor strength was somewhat moderate (24.5%). In the control condition, changes in objective measures induced by the fatiguing work were also relatively small. The largest changes over the fatiguing work were 12.0% for MV_{AP} and 3.5% for DFA_{AP}. Only SA showed a more substantial effect of fatigue (37.4%). In a previous unpublished study, the author investigated the influence of LMF at four body locations on the association between subjectively perceived stability and objective measures of postural control. A larger correspondence between fatigue-related changes in subjective and objective measures was found for conditions involving LMF of the lumbar extensors versus other joints (unilateral ankle, knee, and shoulder); this was consistent for both young and older participants. LMF of the lumbar extensors also resulted in largest changes in objectives measures, suggesting suggests that subjective perceptions of postural stability may be dependent on the magnitude of decrements in postural control induced by LMF, i.e. the larger the decrement in postural control, the better these changes are perceived.

To further analyze results among participants in the break subgroup, fatigue phase standing trials in the rest breaks condition were subdivided as follows: no break trials (no rest breaks were provided afterward), pre-break trials (rest breaks provided immediately afterward), and post-break trials (trials immediate after rest breaks). Compared to no break trials, the pre-break trials had (qualitatively) larger increases in MV and SA, and larger decreases in PS compared to pre-fatigue measures (Figure 4.4). This pattern of results suggests that a subgroup of participants could perceive the decrements in the objective postural control measures. Further, the smallest increases in MV and SA were observed in the post-break trials, accompanied by increases in PS, suggesting that rest breaks could help improve postural control and that such improvement could be perceived. These findings, though not significant, do indicate a potential beneficial effect of rest breaks scheduled according to the decrements in subjective PS on postural control. However, and consistent with earlier evidence of important individual differences in the effects of fatigue and interventions on postural control (Singh et al. 2009), rest breaks may be effective only for a subset of individuals.

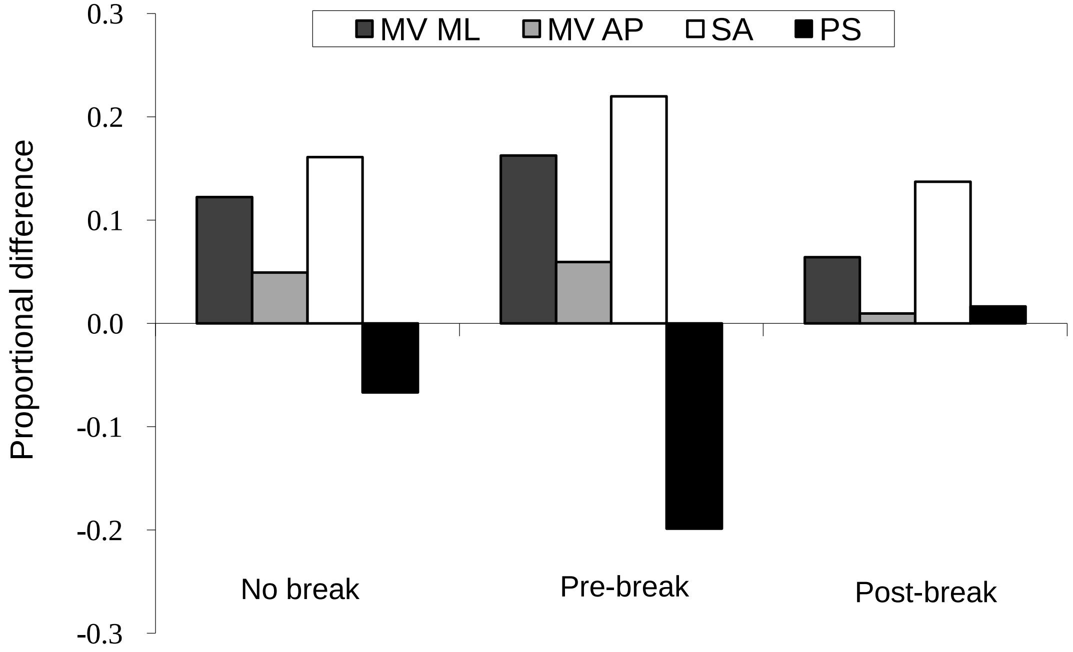

Figure 4.4 Means of proportional differences in several postural control measures among the break group in the rest breaks condition. Errors bars not shown for clarity (SD range = 0.053 ~ 0.582).

4.5.2 Effects of Static Pure Tone

Application of static pure tone during the quiet standing yielded expected improvements in postural control, specifically causing smaller post-fatigue increases in SA and DFA_{AP} and larger decreases in DFA_{ML}. This finding is consistent with the work of Easton et al. (1998), who evaluated the effects of stationary auditory stimulation in sighted and blind individuals and found that symmetric bilateral auditory stimulation reduced postural sway in a tandem Romberg stance for both groups. Use of symmetric bilateral auditory stimulation was justified by one property of human auditory perception. Specifically, Oldfield and Parker (1984) indicated large errors in sound localization when a sound was presented anteriorly or posteriorly, but no error when a sound was presented laterally, which suggests that symmetrical bilateral auditory stimulation can effectively facilitate spatial orientation and help improve postural control.

It was expected, however, that the symmetrical static pure tone used in the current study would have a more substantial effect on postural control in the lateral (ML) vs. sagittal (AP) direction. Although no significant difference in MV_{ML} was found between the control, static pure tone, and moving conversation conditions, the result was suggestive ($p = 0.06$). To further analyze the effects of the static pure tone, a paired *t*-test was performed on MV_{ML}, and indicated a significant difference between the control and static pure tone condition ($p = 0.04$). Compared to the control condition, the static pure tone reduced the fatigue-induced increase in MV_{ML} by 44.5%, whereas the reduction was only 31.5% in the AP direction, confirming the (somewhat) greater stabilizing effect of a symmetrical static pure tone in the lateral direction.

4.5.3 Effects of Moving Conversation

Moving conversation led to stabilizing effects on postural control throughout the fatiguing task, indicated by smaller increases in MV_{AP} and SA, and a larger decrease in DFA_{ML}. This finding is contradictory to our initial hypothesis. Existing evidence regarding the effects of moving auditory stimulation on postural control is inconsistent, and suggests that effects depend largely on the type of auditory stimulation and the manner of presentation. Soames and Raper (1992) found increased postural sway from several conditions involving moving auditory inputs involving both a pure tone and general background conversation. Tanaka et al. (2001) showed that a lateral moving white noise presented via headphone resulted in larger postural sway in older than in younger individuals. However, without a control condition, it is unknown whether such moving white noise has an adverse effect on postural control. Agaeva et al. (2006)

investigated the effects of sound bursts moving sequentially among 53 speakers located uniformly over an arc in the vertical plane and found decreased COP amplitude for a range of moving rates. Deviterne et al. (2005) reported that a rotary auditory stimulation with a meaningful message produced decreased postural sway, which indicated improved quality of postural control.

In the current study, recorded conversation moved among the four speakers randomly at a frequency of 0.2 Hz, which may be too low to mimic a truly random background conversation. Further, the location of the auditory source changed every five seconds, a duration which may have enabled participants to focus on the meaning of the conversation. A few participants reported finding the topic of conversation interesting, though they were instructed to concentrate on standing as still as possible. As suggested by Deviterne et al. (2005), such meaningful conversation could also add cognitive load. Though contradictory findings exist in the literature regarding the effects of cognitive resources on postural control, improved postural control has been reported when a concurrent cognitive task was present (Kerr et al., 1985; Njiokiktjien, 1973; Vuillerme et al., 2000). Thus, the cognitive load added by the current moving conversation may explain the beneficial effects on postural control found here.

One potential concern is a gender difference in fatigability of the lumbar extensors (Larivière et al., 2006). Strength decreases (ΔMVIC) in the lumbar extensors were comparable between the two genders (unpaired *t*-test; $p = 0.15$), with mean decreases of 20.2% for males and 28.7% for females. Regarding the effects of rest breaks, additional analyses including gender into original statistical models led to the same pattern of results with no main effects of gender. For the effects of auditory stimulations, there was significant interaction effects of gender × condition on

SA and PS. This was a quantitative effect only, in which the patterns were similar between genders. Overall, these additional results indicate a minimal modifying influence of gender on the effects of the primary independent variables.

4.5.4 Limitations

There are several limitations to the current study that should be considered. First, it was assumed that the repetitive handling task would induce fatigue mainly at the lumbar extensors. However, some level of fatigue in other muscles as well as global fatigue could not be avoided. Actually, some participants reported discomfort for other muscle groups, including the shoulders, upper back, and legs. Increases in HR also indicated that the general physical fatigue was present in the current study. However, fatigue in other muscles and global fatigue are likely to lead to the same adverse postural effects as from the assumed localized fatigue at the lumbar extensors. Second, as the experiment was not conducted in an anechoic room the auditory signals may have been “contaminated” due to reverberation. Since occupational settings are rarely anechoic, however, the current findings regarding the effects of two auditory stimulations are still considered practically relevant. Third, the findings of this study may only suggest the short-term beneficial effects of the investigated interventions, which may not be present for a long-term period due to adaptation or acclimatization. The long-term effects of these interventions still need to be determined. Fourth, the study results may not be general with respect to fatiguing occupational tasks. Although designed to evaluate interventions in relatively realistic conditions, the current study involved only a single, controlled repetitive lifting/lowering task. Future work should to evaluate the interventions under a range of simulated or actual occupational tasks. The auditory stimulations used in this study were also controlled in terms of specific frequency, loudness, presentation manner, and content. Future studies are needed to assess other types of auditory signals and underlying mechanisms. Finally, generalization to other populations is unknown (individuals differing in age, presence of pathologies, etc.).

4.6 Summary

The efficacy of three interventions at mitigating the adverse effects of muscle fatigue on postural control was examined in this study. Both static pure tone and moving conversation showed stabilizing effects on postural control, offsetting changes induced by a fatiguing lifting/lowering task. Though allowance of rest breaks did not provide beneficial effects overall, there was a suggestion that such an intervention might be of value among a subset of individuals. These findings can aid in the development of future practical interventions to reduce the risk of falls, though further work is still warranted to elucidate their effectiveness and underlying mechanisms.

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Chapter 5: Conclusions

Falls in the workplace remain a significant cause of injuries and fatalities. Among a number of identified risk factors, muscle fatigue is one important task-related factor that has been linked to a decrement in postural control and a potential increased risk of falling. Although the adverse effects of muscle fatigue have been well documented, there is still a need to understand how muscle fatigue interacts with other factors to affect postural control. Specifically, many occupational settings require workers to perform tasks involving standing on inclined surfaces or manual materials handling (MMH). Inclined surface have been associated with an increased slipping risk, as well as decreased postural control performance. Lifting unexpected loads have also been demonstrated to compromise posture control. However, whether there are interactive effects of muscle fatigue with these risk factors remains unclear. In addition, interventions that can be easily implemented in realistic occupational settings are still needed to mitigate the adverse effects of muscle fatigue on postural control. The current work was conducted to address these research needs through three experimental studies.

5.1 Research Contribution

The results of the first study provided fundamental evidence on the differential effects of inclination directions and muscle fatigue effects on postural control in the presence of inclination. These findings have several practical implications. The differential effects of inclination direction suggest that tasks involving standing on laterally inclined surfaces may lead to a higher falling risk than those on the sagittally-inclined surfaces. Thus, work involving such lateral conditions should be particularly avoided. The increasingly detrimental effect of inclination angle on postural control suggests that working surfaces should be horizontal where possible, or minimized otherwise. The consistent deleterious effects of localized muscle fatigue across a range of inclination conditions implies that fatigue should be minimized regardless of the specific task demands or environment. These recommendations may be possible to achieve through task redesign, education, and training programs.

The second study provided fundamental evidence on the effects of muscle fatigue on postural control during relatively realistic load lifting tasks. Such information may lead to practical application to help prevent and reduce fall-related injuries due to load handling and/or associated with fatigue. An incorrect estimation of the mass of an object to be lifted clearly compromised postural control and led to an increased falling risk. The differential effects of two unexpected conditions suggested that lifting an unexpectedly light object may lead to a higher falling risk than an unexpectedly heavy object. Education or training programs may be developed based on such information, for example by emphasizing the possibility of injury resulting from incorrect load estimation during lifting, especially the higher risk of overestimation. Benefits may also be provided by training workers to perform adequate preparations in situations where only visual information of loads is available. Lumbar extensor fatigue did not further compromise postural control during lifting an unexpected load, suggesting that muscle fatigue, at least at the location and level investigated here, may not be a major contributing risk factor during MMH tasks.

The last study evaluated the efficacy of three interventions aimed at mitigating the adverse effects of muscle fatigue on postural control. The first intervention provided periodic rest breaks scheduled according to subjective perceptions of decrements in postural stability, while the other two involved auditory stimulations (static pure tone and moving conversation). Allowance of rest breaks did not improve postural control throughout the fatiguing work, though there was a trend indicated an offset in fatigue-induced decreases in subjective perception of stability. Both the static pure tone and moving conversation showed stabilizing effects on postural control, offsetting changes induced by a fatiguing lifting/lowering task.

Although this was an exploratory study, the findings of the last study suggest the potential application of the investigated interventions towards reduction of occupational injuries and fatalities resulting from falls. The current interventions can be easily implemented in some realistic occupational settings. For example, symmetric bilateral pure tones can be used for the tasks that require workers to be in a relatively fixed location. A meaningful conversation background may be applied in some work settings without much noise. Although the potential effects still need further investigation, periodic rest breaks can be employed in any situation where rest breaks are possible throughout the workday. Subjective perceptions can be collected and brief rest breaks can be provided at intervals during the day.

Overall, the current research provided a more comprehensive understanding of the contribution of muscle fatigue to fall risks during occupationally relevant tasks and helped determine the efficacy of practical interventions to reduce risk of falls. These findings may facilitate the development of strategies to prevent occupational falls related to muscle fatigue, inclined surfaces, and manual material handling tasks.

5.2 Future Directions

Several research issues, which are not completely addressed in this work, remain for future investigations. First, the initial two studies focused on the effects of lumbar muscle fatigue, which was induced by tightly controlled exercise. Future studies should be conducted to determine whether comparable effects result from additional or more complex fatigue conditions and fatigue of other muscle groups.

Second, the current work is an initial step toward developing simple and effective interventions that can be feasibly applied to occupational settings. Although both static pure tone and moving conversation were found to improve postural control during a simulated fatiguing task, the effects of auditory stimulations are dependent on frequency, loudness, presentation manner, and content. Thus, future studies are needed to assess other types of auditory signals and underlying mechanisms. Though allowance of rest breaks did not show a beneficial effect on postural control overall, there was an indication that this might be effective for certain individuals. Thus, the effects of rest breaks scheduled based on perceived stability need further investigation.

Finally, the participants in the current work were all young, healthy individuals. Future studies are needed to investigate whether the current findings would be present in other populations (individuals differing in age, presence of pathologies, etc.).

Appendix A: Informed Consent Form for Study 1

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

Informed Consent for Participants
In Research Projects Involving Human Subjects

Title of the Research Study

Interaction effects of inclined surfaces and muscle fatigue on postural control

Investigators

Maury A. Nussbaum, Ph.D. 540-231-6053 – Department of Industrial and Systems Engineering
Dingding Lin, Ph.D. Candidate 540-239-1598 – Department of Industrial and Systems Engineering

I. Purpose of this Research Project

Falls are a major cause of work-related injuries and fatalities and have adverse impacts in terms of economic cost and workers' health. Both muscle fatigue and standing on inclined surfaces have been shown to adversely affect balance. The purpose of this research study is to better understand how fatigue of the low back muscles along with standing on inclined surfaces affects balance. The findings from this research study will provide a better understanding of contribution of muscle fatigue and inclination on occupational falls, and contribute to the development of practical interventions aimed at decreasing the risk of falls.

A total of 18 adult participants will be used for this study, including 9 young males (18-24 years old) and 9 young females (18-24 years old). Participants should have no occurrences of falls in the past year, be free of any musculoskeletal / neurological disorders or injuries that may adversely impact your balance or ability to perform the fatiguing exercises, and participate in moderate levels of physical activity.

II. Procedures

The study will take place in the Industrial Ergonomic Lab (Department of Industrial and Systems Engineering). You will be asked to complete the experiment in 3 separate occasions, one for each inclination angle (0°, ~18°, and ~ 26°). Each of these will be on different days separated by at least 48 hours.

During the first session, upon arriving, you will be briefed of the study protocol, asked if you have any further questions, and asked to sign this informed consent form. Then, you will be asked to complete a screening questionnaire to determine your eligibility.

Prior to the experiment, several markers will be placed on your skin surface using double-sided tape, and will be used to analyze your movement patterns during the experiment. Measures of your bodily dimensions will also be obtained (e.g. height and weight).

At the start of the experiment, balance will be measured while you are unfatigued. These balance measures will include: 1) measures obtained from a specialized platform and a marker tracking system while you stand still for 75 seconds, and 2) your perceived steadiness. During the balance measurement, you will be asked to stand still on a plywood platform with different inclination angles and facing different direction. You will be asked to perform multiple balance trials before fatiguing exercises. Then, the strength of your lower torso muscles will be measured. Following the strength measurement, you will perform a back extension exercise on a Biodex System (similar to a health club-type exercise apparatus) to fatigue the muscles in your lower back. Immediately following this exercise, strength will be measured again and then you will return to the force platform to perform three balance trials using one inclination direction. At this time, balance measurements will be performed identically to the initial measurement procedure. The back extension exercises, strength measurement, and three balance trials will be repeated two more times for two other inclination directions. The experiment is expected to take approximately 2 - 3 hours to complete.

III. Risks

The risks to being involved in this study are minimal. The overall physical exertion required during this experiment is not significantly larger than that required during common manual labor. There is some chance that you may feel delayed muscle stiffness or soreness in 1-2 days after participation, similar to what you would experience following recreational exercise.

IV. Benefits

You will receive no direct benefit from participating in this study. The scientific community will benefit through the additional information that is expected to result from the completion of this study. This information will contribute to fall-related biomechanical knowledge that will be used to develop intervention techniques to prevent falls from heights.

No promise or guarantee of benefits has been made to encourage you to participate.

V. Extent of Anonymity and Confidentiality

The results of this research study may be presented at meetings or in publications. Your identity will not be disclosed in those presentations. All participants will be identified based only on their unique identifying number. Only the investigators involved in the research will have access to these identifying numbers. Data will be destroyed after the completion of the study and the defense of the dissertation, and publication of any associated journal and conference papers.

It is possible that the Institutional Review Board (IRB) may view this study's collected data for auditing purpose. The IRB is responsible for the oversight of the protection of human subjects involved in research.

VI. Compensation

You will be paid $10/hour for your participation in this study. A bonus in the amount of $10.00 will be provided at the completion of this study.

VII. Freedom to Withdraw

Your participation in this research study is voluntary. Refusal to participate will involve no penalty or loss of benefits to which you are otherwise entitled. You are free to withdraw from the study at any time without penalty. If you choose to withdraw, you will be compensated for the portion of the time of the study. You are free not to answer any questions or respond to experimental situations that you choose without penalty.

VIII. Approval of Research

This research project has been approved, as required, by the Institutional Review Board for Research Involving Human Subjects at Virginia Polytechnic Institute and State University.

IRB Approval Date: __________________

Approval Expiration Date: ____________________

IX. Participant Responsibilities

I voluntarily agree to participate in this study and to follow the responsibilities listed below:

a. To inform the investigator/experimenter as early as possible about a desire to discontinue participation in the study.

b. To inform the investigator of any medical conditions that might be adversely affected by the experiment, or those that might interfere with results of the experiment.

X. Participant's Permission

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

Participant signature Date

Witness Date

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

Investigator:
Dingding Lin, Ph.D. candidate 540-239-1598 lindd@vt.edu

Faculty Advisor:
Maury Nussbaum, Ph.D. 540-231-6053 nussbaum@vt.edu

Departmental Reviewer/Department Head:
Thurmon Lockhart, Ph.D. 540-231-9088 lockhart@vt.edu

Chair, Virginia Tech Institutional Review Board for the Protection of Human Subjects
David M. Moore 540-231-4991/moored@vt.edu

Appendix B: Informed Consent Form for Study 2

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

Informed Consent for Participants
In Research Projects Involving Human Subjects

Title of the Research Study

Effects of Muscle Fatigue and Unexpected Loads on Balance while Lifting

Investigators

Maury A. Nussbaum, Ph.D. 540-231-6053 – Department of Industrial and Systems Engineering
Dingding Lin, Ph.D. Candidate 540-239-1598 – Department of Industrial and Systems Engineering

I. Purpose of this Research Project

Falls are a major cause of work-related injuries and fatalities and have adverse impacts in terms of economic cost and workers' health. Both muscle fatigue and manual material handling activities have been shown to adversely affect balance. The purpose of this research study is to better understand how fatigue of the low back muscles affects balance during lifting loads. Findings from this research study will provide a better understanding of the contribution of muscle fatigue to occupational falls, and contribute to the development of practical interventions aimed at decreasing the risk of falls.

A total of 16 adult participants will be used for this study, including 8 young males (18-24 years old) and 8 young females (18-24 years old). Participants should have no occurrences of falls in the past year, be free of any musculoskeletal / neurological disorders or injuries that may adversely impact your balance or ability to perform the fatiguing exercises and lifting tasks, and participate in moderate levels of physical activity.

II. Procedures

The study will take place in the Industrial Ergonomic and Biomechanics Lab (Department of Industrial and Systems Engineering). You will be asked to complete one experimental session.

During the experimental session, upon arriving, you will be briefed of the study protocol, asked if you have any further questions, and asked to sign this informed consent form. Then, you will be asked to complete a screening questionnaire to determine your eligibility.

Prior to the experiment, several markers will be placed on your skin surface using double-sided tape, and will be used to analyze your movement patterns during the experiment. Measures of your bodily dimensions will also be obtained (e.g., height and weight).

At the start of the experiment, you will be asked to perform two lifting sets before the fatiguing exercise. Each lifting set will consist of multiple lifting trials with a box weighing either 3 kg or 13 kg. Balance will be measured during these lifting trials using a force platform and a marker tracking system. For the lifting trial, you will lift a box, which will be placed in front of your feet, from the ground to your knuckle height. You will be required to use a back lift and perform the lift symmetrically. You will have a 5-minute rest break between the two lifting sets. After the two lifting sets, the strength of your lower torso muscles will be measured. Following the strength measurement, you will perform a back extension exercise on a Biodex System (similar to a health club-type exercise apparatus) to fatigue the muscles in your lower back. Immediately following this exercise, your low back strength will be measured again and then you will return to the force platform to perform multiple lifting trials using the same lifting protocol with a box weighing either 3 kg or 13 kg. The load mass will be changed without notifying you in advance. This experiment is expected to take approximately 2-3 hours to complete.

III. Risks

The risks with being involved in this study are minimal. The overall physical exertion required during this experiment is not significantly larger than that required during common manual labor. During the experiment you will perform exercises that will lead to muscle fatigue, and there is a small change of "pulling" a muscle. There is some chance that you may feel delayed muscle stiffness or soreness over 1-2 days after participation, similar to what you would experience following recreational exercise.

IV. Benefits

You will receive no direct benefit from participating in this study. The scientific community will benefit through the additional information that is expected to result from the completion of this study. This information will contribute to fall-related biomechanical knowledge that will be used to develop intervention techniques to prevent occupational falls.

No promise or guarantee of benefits has been made to encourage you to participate.

V. Extent of Anonymity and Confidentiality

The results of this research study may be presented at meetings or in publications. Your identity will not be disclosed in those presentations. All participants will be identified based only on their unique identifying number. Only the investigators involved in the research will have access to these identifying numbers. Data will be destroyed after the completion of the study and the defense of the dissertation, and publication of any associated journal or conference papers.

It is possible that the Institutional Review Board (IRB) may view this study's collected data for auditing purpose. The IRB is responsible for the oversight of the protection of human subjects involved in research.

VI. Compensation

You will be paid $10/hour for your participation in this study. A maximum of $30 (for three hours of participation) will be provided for compensation.

VII. Freedom to Withdraw

Your participation in this research study is voluntary. Refusal to participate will involve no penalty or loss of benefits to which you are otherwise entitled. You are free to withdraw from the study at any time without penalty. If you choose to withdraw, you will be compensated for the portion of the time of the study. You are free not to answer any questions or respond to experimental situations that you choose without penalty.

VIII. Approval of Research

This research project has been approved, as required, by the Institutional Review Board for Research Involving Human Subjects at Virginia Polytechnic Institute and State University.

IX. Participant Responsibilities

I voluntarily agree to participate in this study and to follow the responsibilities listed below:

a. To inform the investigator/experimenter as early as possible about a desire to discontinue participation in the study.

b. To inform the investigator of any medical conditions that might be adversely affected by the experiment, or those that might interfere with results of the experiment.

X. Participant's Permission

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

____ _______________

Participant signature Date

____ _______________

Witness Date

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

Investigator:
Dingding Lin, Ph.D. candidate 540-239-1598 lindd@vt.edu

Faculty Advisor:
Maury Nussbaum, Ph.D. 540-231-6053 nussbaum@vt.edu

Departmental Reviewer:
Thurmon Lockhart, Ph.D. 540-231-9088 lockhart@vt.edu

Chair, Virginia Tech Institutional Review Board for the Protection of Human Subjects
David M. Moore 540-231-4991/moored@vt.edu

Appendix C: Informed Consent Form for Study 3

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

Informed Consent for Participants In Research Projects Involving Human Subjects

Title of the Research Study

Project 3 – Evaluation of Control Strategies to Improve Balance
Experiment 2 – Use of Auditory Stimulation and Perceived Steadiness

Investigators

Maury A. Nussbaum, Ph.D. 231-6053 – Department of Industrial and Systems Engineering
Michael L. Madigan, Ph.D. 231-1215 – Department of Engineering Science and Mechanics

I. Purpose of this Study

Falls from heights are a major problem in both industry and general society when measured in terms of human suffering and economic losses. Muscle fatigue has been recently shown to adversely affect balance, and the purpose of this research study is to evaluate three interventions to reduce the adverse effects of fatigue on balance during simulated work activities. The three interventions will be a static pure tone, moving conversation, and periodic rest breaks scheduled according to perceived steadiness. The findings from this research study will contribute to the development of practical interventions aimed at minimizing the effect of fatigue on balance and decreasing the risk of occupational falls.

II. Procedures

A total of 32 adult participants are anticipated for the study. The study will take place in the Industrial Ergonomic Lab (Department of Industrial and Systems Engineering). Upon arriving, you will be briefed of the study protocol, asked if you have any further questions, and asked to sign this informed consent form.

Prior to the experiment, several non-invasive position sensors will be placed on your body using double-sided tape. The experimental session will be videotaped to help the investigators analyze your movement patterns during the experiment. Measures of your bodily dimensions will also be obtained (e.g. height and weight).

At the start of the experiment, balance will be measured while you are unfatigued. These balance measures will include: 1) measures obtained from a specialized platform while you stand still for 75 seconds, and 2) your perceived steadiness. You will then perform simulated work activities (lifting/lowering) for a period of up to two hours. At 15-minute intervals, the activities will be interrupted to measure balance during standing.

You will be asked to complete four separate experimental sessions, one without any intervention, one with a static pure tone, one with moving conversation, and one with periodic rest breaks. During the experiment with a static pure tone, a tone will be presented from two speakers while you stand quietly. This tone will have a frequency of 250 Hz (similar to middle C note) and an intensity of 60 dB (similar to normal conversation at 1 m). During the experiment with moving conversation, general conversation will be presented from several speakers, again while you stand quietly. During the experiment with rest breaks, you will be given a brief rest break whenever your perceived steadiness decreases substantially from its initial value. During the experiment without rest breaks, you will immediately return to the simulated work activities after the balance measurements. The four experimental sessions will be separated by at least two days and performed in a different order for each participant.

III. Risks

The risks to being involved in this study are minimal. The overall physical exertion required during this experiment is not significantly larger than that required during common manual labor, and will be performed for a much shorter duration. There is some chance that you may feel some degree of stiffness or muscle soreness 1-2 days after participation, similar to what you would experience following exercise.

IV. Benefits

You will receive no direct benefit from participating in this study. The scientific community will benefit through the additional information that is expected to result from the completion of this study. This information will contribute to fall-related biomechanical knowledge that will be used to develop intervention techniques to prevent falls from heights.

No promise or guarantee of benefits has been made to encourage you to participate.

V. Extent of Anonymity and Confidentiality

The results of this research study may be presented at meetings or in publications. Your identity will not be disclosed in those presentations. All participants will be identified based only on their unique identifying number. Only the investigators and students involved in the research will have access to these identifying numbers. The video recordings from this study will be analyzed and stored in the labs under the supervision of the investigators. Some photographs or video recordings may be shown to other scientists at the University or at scientific conferences, but only after identifying information is removed (e.g. we would block out faces).

VI. Compensation

You will be paid $10/hour for your participation in this study.

VII. Freedom to Withdraw

Your participation in this research study is voluntary. Refusal to participate will involve no penalty or loss of benefits to which you are otherwise entitled. You are free to withdraw from the study at any time without penalty.

VIII. Approval of Research

This research project has been approved, as required, by the Institutional Review Board for Research Involving Human Subjects at Virginia Polytechnic Institute and State University.

IRB Approval Date: ___________________

Approval Expiration Date: _____________________

IX. Participant Responsibilities

I voluntarily agree to participate in this study.

X. Participant's Permission

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

____ ________________

Participant signature Date

____ ________________

Witness Date

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

<u>Principal Investigator</u>:	Maury Nussbaum, PhD	231-6053	nussbaum@vt.edu
<u>Co-Investigator</u>:	Michael Madigan, PhD	231-1215	mlmadigan@vt.edu
<u>Chair, IRB</u>:	David M. Moore, DVM	231-4991	moored@vt.edu