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Influence of fatigue time and level on increases in postural sway

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The purpose of this study was to investigate the influence of fatigue time and fatigue level on the increases in postural sway during quiet standing. Centre of pressure-based measures of postural sway were collected both before and after fatiguing participants using three different fatigue levels and two different fatigue times. Results showed increasing fatigue time increased sway velocity and sway area, and increasing fatigue level increased sway velocity. Fatigue time effects are important to consider when applying laboratory-based findings to the field given that the fatigue time can differ substantially between the two. Fatigue level effects imply a dose–response relationship between localized muscle fatigue and risk of falling that can have important implications in work/rest cycle scheduling for occupations at risk of injurious falls.

Keywords: Accidental falls; Muscle fatigue; Postural balance

1. Introduction

Localized muscle fatigue (LMF) may increase the risk for falling. For example, postural sway increases with LMF at the ankle (Yaggie and McGregor 2002, Vuillerme *et al.* 2002, 2003, Caron 2003), at the knee and hip (Gribble and Hertel 2004), in the lumbar extensors (Davidson *et al.* 2004) and at the shoulder (Nussbaum 2003). Increases in postural sway are thought to indicate an impairment of postural control and are associated with increased fall rates (albeit in older adults) (Overstall *et al.* 1977, Fernie *et al.* 1982, Lichtenstein *et al.* 1988, Maki *et al.* 1994). Therefore, the increases in

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postural sway with LMF suggest an increased risk for falling. Additional studies are needed to understand how other factors may influence the effects of LMF on sway. Ultimately, this information can be used to help develop interventions aimed at reducing the effects of LMF on risk of falling. This is particularly important for occupations such as roofing, where fatigue is common and falls can be fatal (Hsiao and Simeonov 2001).

One factor that may influence the effects of LMF on sway, and therefore the risk of falling, is the time over which LMF is induced (fatigue time). Outside the laboratory, LMF is frequently induced at a relatively low workload over a period of several hours. Inside the laboratory, LMF is typically induced at a relatively high workload over a period of several minutes (Sparto *et al.* 1997, Yaggie and McGregor 2002). It is important to recognize if fatigue time influences the effects of LMF on sway if laboratory-based findings are to be applied to the workplace. Davidson *et al.* (2004) fatigued the lumbar extensor muscles to 60% of their unfatigued maximum voluntary contraction (MVC) force over 11 min and 90 min. Standing postural sway increased with fatigue, but there was no differential effect of fatigue time. It was noted, however, that the statistical power for this test was low and a qualitative trend did exist in which sway tended to recover more quickly after the 11 min fatigue time compared to the 90 min fatigue time. The present work re-examined this trend using an improved fatigue protocol to elicit more controlled levels of lumbar extensor fatigue and included more frequent sway measurements for the 30 min after the fatigue protocol. Both of these improvements should help offset the high variability of traditional centre of pressure (COP)-based sway measurements and therefore improve the statistical power for finding an effect of fatigue time. The null hypothesis tested was that varying fatigue time would not influence the increase in sway with LMF.

Another factor that may influence the effects of LMF on sway is the amount of fatigue induced (fatigue level). If higher levels of LMF result in larger increases in sway, this 'dose – response relationship' would imply that higher levels of LMF are associated with higher risk of falling. Few studies have directly investigated a dose – response relationship between physiological or biomechanical measures of muscle function and fatigue, but such a relationship can be inferred from studies that have employed sustained or repeated contractions (Bigland-Ritchie *et al.* 1986, Hunter and Enoka 2003). Based on these studies, it seems plausible that a dose – response relationship could exist between fatigue and postural sway. The authors are unaware of any studies that have investigated the effects of fatigue level on postural sway. Therefore, the present study also investigated this following lumbar extensor fatigue. The null hypothesis tested was that varying fatigue level would not influence the increase in sway with LMF.

2. Methods

A total of 12 physically active males (20–22 years of age) participated in the experiment. Mean participant stature and mass were 173.7 (SD 6.4) cm and 70.2 (SD 6.6) kg, respectively. None of the participants reported any history of low back pain or injury and all provided informed consent in accordance with the Virginia Tech Institutional Review Board before participation.

Four experimental sessions were completed by each participant with at least 1 week between consecutive sessions. During each session, postural sway during quiet standing was recorded before and intermittently for 30 min after a lumbar extensor fatigue protocol. The fatiguing protocol involved multiple sets of back extensions and systematic adjustment of the number of repetitions in each set to fatigue each participant to a specific fatigue level over a specific fatigue time. In three of the experimental sessions, the participant was fatigued over 14 min to 86% of their unfatigued lumbar extensor MVC torque (low-14) to 73% of their unfatigued MVC torque (moderate-14) and to 60% of their unfatigued MVC torque (high-14), respectively. In the fourth session, each participant was fatigued over a fatigue time of 90 min to 73% of their unfatigued MVC torque (moderate-90). The presentation order of the four fatigue conditions (low-14, moderate-14, high-14, moderate-90) was balanced using a 4×4 balanced Latin square replicated three times.

After a brief warm-up, participants were fitted into a safety harness and positioned on a 45° Roman chair (New York Barbell, Elmira, NY, USA) as shown in figure 1. Three unfatigued isometric MVCs of the lumbar extensors were performed by instructing participants to extend at the back as hard as possible while pulling against a load cell (Cooper, Warrenton, VA, USA) that anchored the safety harness to the Roman chair (figure 1). Consecutive MVCs were separated by 1 min of rest. Using the load cell data and an estimation of head, arms and trunk mass and centre of mass position to correct for gravitational force on the upper body (de Leva 1996), the corresponding torque at the 'lumbar joint' (approximately between the intervertebral discs L3 and L4) was estimated for all MVCs. The largest of the three MVCs was recorded as the unfatigued MVC value.

The fatigue protocol consisted of multiple sets of back extensions performed on the 45° Roman chair (Davidson *et al.* 2004). Prior to performing the back extensions, participants were instructed to move through approximately a 60° range of motion, from 0° back extension to their maximum flexion. A digital metronome set at 30 beeps/min was used to ensure all participants performed the extensions at a consistent rate. Participants were allowed to stand and stretch between sets if time permitted.

Investigators attempted to fatigue participants such that their lumbar extensor MVC torque decreased linearly over the duration of the fatigue protocol and achieved the desired fatigue level over the desired fatigue time (figure 2). One set was performed each

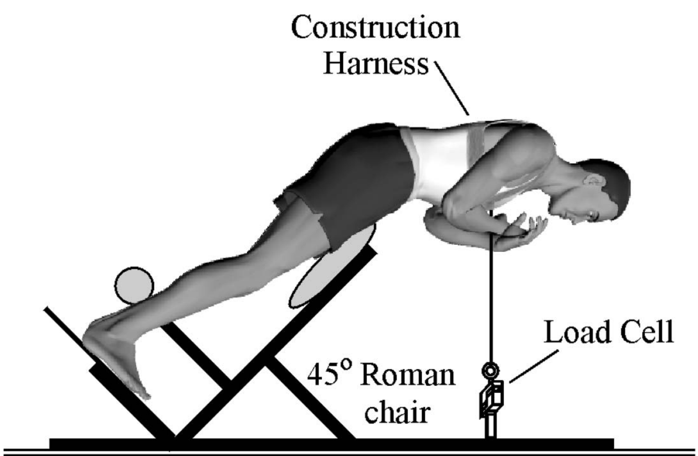

Figure 1. Participant positioned on the Roman chair for measurement of maximum voluntary contractions of the lumbar extensors. Participants also used the Roman chair for back extensions, but during these the load cell was disconnected from the harness to allow greater range of motion.

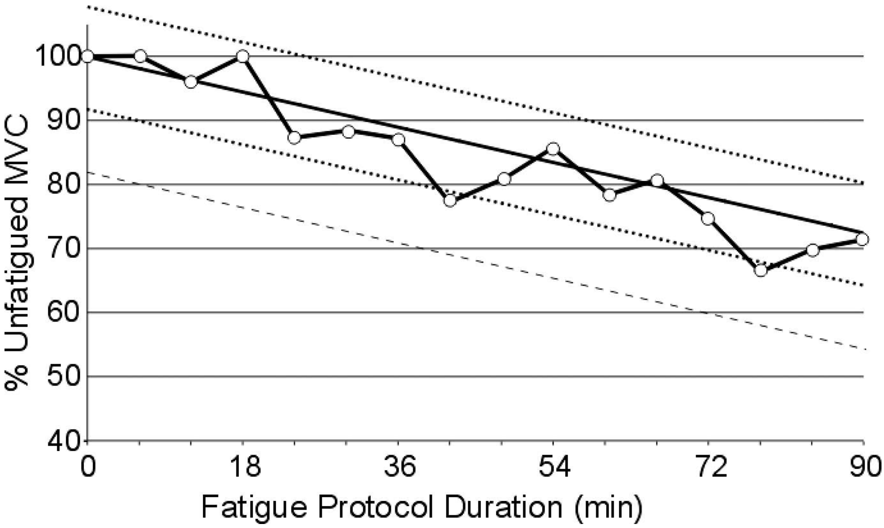

Figure 2. Representative maximum voluntary contraction (MVC) torques during a 90 min fatigue protocol attempting to fatigue the lumbar extensors to 73% of the unfatigued MVC torque. —— represents the target fatigue rate; ······· represents target $\pm 5\%$; - - - - represents -15% guidelines. ○ shows MVC torque measurements collected every 6 min. The number of repetitions in each set was adjusted based on where the measured MVC torques were with regard to these guidelines.

minute and the number of repetitions in each set was systematically adjusted based upon a comparison of the measured MVC torque during intermittent MVCs to the target torque at that time. An MVC was also performed at the end of the fatigue protocol to quantify the participants' level of fatigue. The measured fatigue levels after the experiment were $81.9 \pm 4.5\%$ MVC for low-14, $69.7 \pm 4.5\%$ MVC for moderate-14 and $59.9 \pm 3.4\%$ MVC for high-14 for the first three experimental conditions. These fatigue levels differed significantly from each other ($p < 0.001$). Participants were fatigued to $66.3 \pm 3.4\%$ MVC during the moderate-90 experimental condition, and this fatigue level was not significantly different from that for moderate-14 condition ($p = 0.182$).

Both before and after the fatigue protocol, participants were instructed to 'stand as still and as quietly as possible' for 30 s with their feet together, eyes closed and arms at their sides for postural sway data collections. Three unfatigued postural sway collections were performed before the fatigue protocol, and 11 fatigued collections were performed afterwards (every 3 min for the next 30 min). During each collection, ground reaction forces and moments were obtained using a Bertec K20102 type 9090–15 force platform (Bertec Corp., Columbus, OH, USA). Force platform data were hardware filtered (low-pass, 500 Hz cutoff), amplified, sampled at 1000 Hz, low-pass filtered at 10 Hz (zero-phase-lag 2nd order Butterworth), and transformed into COP data (Winter 1990). Three COP-based measures of postural sway were chosen for analysis including mean velocity, peak velocity and sway area using the 'modified ellipse' algorithm (Prieto *et al.* 1996). Using data from each participant, differences between each fatigued collection and the mean of the three unfatigued collections were calculated for all three measures of postural sway. A 3-point moving average (Kutner *et al*. 2004) was then applied to the difference measures during the recovery period in order to smooth these data. The number of fatigued sway measurements was therefore reduced from 11 to nine, representing times from 3 min after the fatigue protocol to 27 min after the protocol.

Two separate statistical analyses were performed to investigate changes in sway immediately after the fatigue protocol, and changes in sway during the 30 min after the fatigue protocol (i.e. during fatigue recovery). To determine the effect of lumbar extensor fatigue on sway immediately after the fatigue protocol, a one-sample t-test (test value = 0) was used with data from the first fatigued collection (after the moving average) pooled across the four fatigue conditions. To determine the effect of fatigue time and fatigue level on sway immediately after the fatigue protocol, a one-way repeated measures ANOVA was used with fatigue condition as the independent variable (four levels: low-14; moderate-14; high-14; moderate-90). In the event of a significant fatigue condition effect, pairwise comparisons were performed using a Tukey HSD between moderate-14 and moderate-90 to investigate a fatigue time effect, and between low-14, moderate-14 and high-14 to investigate a fatigue level effect. To determine the effect of fatigue time and fatigue level on sway during recovery from fatigue, a two-way repeated measures ANOVA was used with independent variables of fatigue condition and time (nine levels: 3–27 min in 3 min increments). In the event of a significant fatigue condition or interaction effect, pairwise comparisons were performed using a Tukey HSD. In the event of a significant time effect, a one-sample t-test was used to determine at which times the change in sway was significantly different from zero (i.e. significantly different from the unfatigued value).

A significance level of $p = 0.05$ was used for all statistical tests, and a Bonferroni correction was used for the one-sample t-tests for protection against Type I error. All statistical analyses were performed using JMP IN (SAS Institute Inc., Cary, NC, USA).

3. Results

Immediately after the fatigue protocol, fatigue and fatigue level both affected postural sway. Fatigue increased mean sway velocity 11.8% ($p < 0.001$) and increased peak sway velocity 15.3% ($p < 0.001$), but did not affect sway area ($p = 0.253$). The only fatigue level effect was a significantly higher peak sway velocity ($p < 0.05$) for high-14 (fatigued to 60% MVC torque over 14 min) compared to low-14 (fatigued to 86% MVC torque over 14 min). Fatigue time had no effect on sway measured immediately after the fatigue protocol.

During the 30 min following the fatigue protocol, time, fatigue time and fatigue level all affected postural sway. There were no significant interactions, indicating no significant difference in how the four fatigue conditions varied over time. Time affected postural sway in that mean sway velocity and peak sway velocity took approximately 15 and 9 min, respectively, until they were not significantly different from unfatigued values (figure 3). Sway area was not affected by time ($p = 0.710$). Fatigue time affected postural sway in that moderate-90 (fatigued to 73% MVC torque over 90 min) exhibited higher mean sway velocity ($p < 0.05$; figure 4), peak sway velocity ($p < 0.05$), and sway area ($p < 0.05$) compared to moderate-14 (fatigued to 73% MVC torque over 14 min). Fatigue level affected postural sway in that high-14 exhibited significantly higher mean sway velocity ($p < 0.05$) and peak sway velocity ($p < 0.05$) compared to the moderate-14 (figure 5). High-14 also exhibited higher peak sway velocity compared to low-14 ($p < 0.05$). Fatigue level had no effect on sway area ($p = 0.253$).

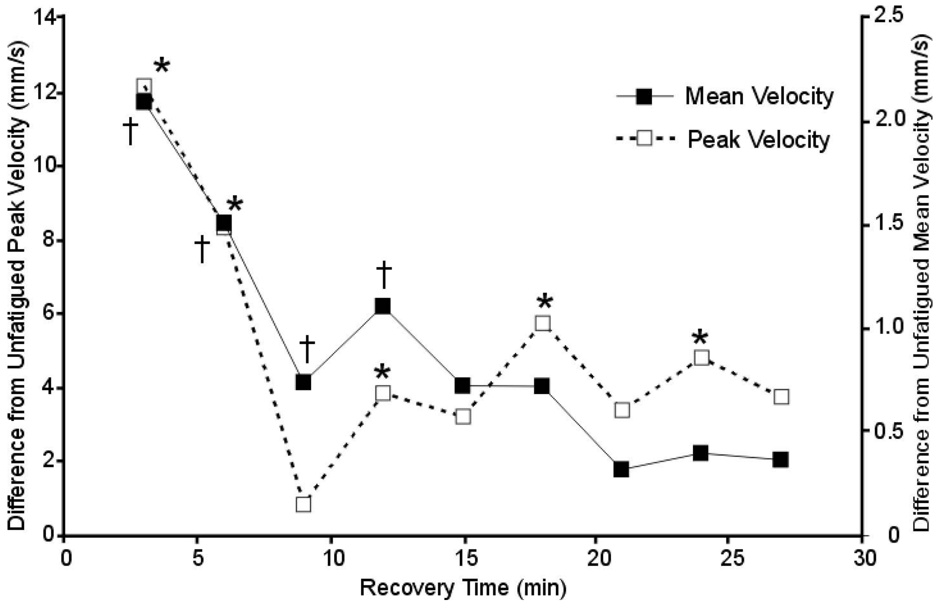

Figure 3. Time course of sway mean velocity and peak velocity averaged across all participants and all four fatigue conditions. *indicates peak velocity is significantly different from zero ($p < 0.006$). †indicates mean velocity is significantly different from zero ($p < 0.006$). Note that peak velocity first becomes not significantly different from zero at 9 min, and mean velocity first becomes not significantly different from zero at 15 min. Error bars were omitted for clarity, but are available from the authors.

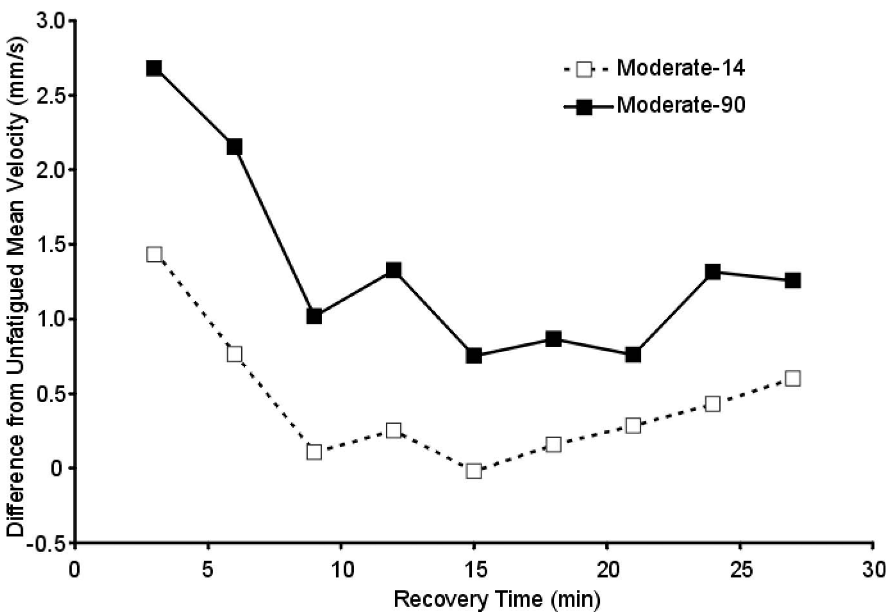

Figure 4. Fatigue time effect on mean sway velocity following lumbar extensor fatigue. The long fatigue time (moderate-90) is significantly greater than the short fatigue time (moderate-14) ($p < 0.05$).

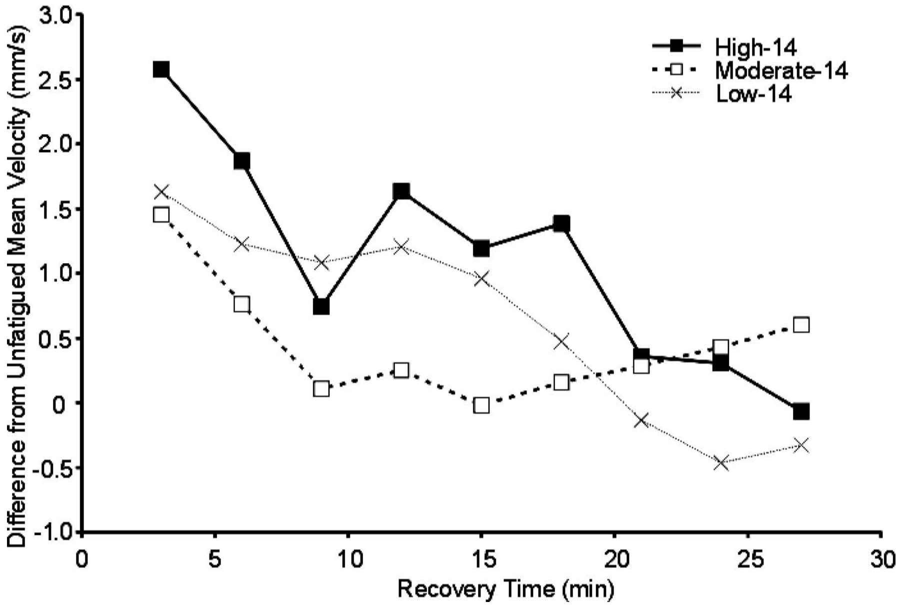

Figure 5. Fatigue level effect on mean sway velocity following lumbar extensor fatigue. The high fatigue level (high-14) is significantly greater than the moderate fatigue level (moderate-14).

4. Discussion

The main objective of this study was to determine the effects of fatigue time and fatigue level on postural sway following lumbar extensor fatigue. The main findings showed larger increases in sway velocity and sway area when fatigue was induced over longer durations, and larger increases in sway velocity at higher fatigue levels. Most of these effects were not detected immediately after the fatigue protocol, but only when considering all data collected for 30 min following the fatigue protocol. This is likely due to the high variability in COP-based measures of postural sway. Analysing sway for 30 min following the fatigue protocol provided additional data to offset this variability and improve the statistical power to find a fatigue time effect. These findings are consistent with those of Davidson *et al.* (2004), who reported no differences in sway immediately after 10 and 90 min fatiguing protocols, but trends toward quicker recovery of sway after the 10 min protocol.

The reason for the higher sway velocity and larger sway area after the long fatigue time may be related to differences in physiological and/or biomechanical responses between the two fatigue times. The loss of force-producing capability with fatigue arises from metabolic and non-metabolic processes (Vollestad and Sejersted 1988). Longer duration exercises are thought to be more heavily influenced by longer-lasting non-metabolic processes that act at the level of excitation–contraction coupling (Edwards *et al.* 1977). As a result, muscle force-producing capability requires longer to recover after longer duration exercises (Baker *et al.* 1993). Although the lumbar extensor force necessary for quiet standing is small, impaired excitation–contraction coupling may contribute to increased force fluctuations (Hunter and Enoka 2003) that in turn leads to increased torso movement and increased sway. The long fatigue time protocol may also result in increased creep in the lumbar spine viscoelastic connective tissue. Participants performed 167 ± 36 back extensions during moderate-14 and 665 ± 169 back extensions during moderate-90 (although both protocols elicited a similar drop in MVC torque). This almost four-fold increase in work performed likely resulted in more creep in lumbar connective tissues (Solomonow *et al.* 2003). Lumbar creep is associated with impaired trunk control as evidenced by smaller reflex responses (Rogers and Granata 2006), and may also have contributed to increased torso movement and the observed increase in sway.

The reason for higher sway velocities with higher levels of lumbar extensor fatigue may also be related to differences in physiological and/or biomechanical responses between the three fatigue levels. These reasons may be similar to those that explain the effects of fatigue time. Muscle force fluctuations increase during submaximal contractions sustained to exhaustion (Hunter *et al.* 2004). Based on this, it appears that increased levels of fatigue lead to increased muscle force fluctuations. An increase in lumbar extensor force fluctuations would likely lead to increased torso movement and a concomitant increase in postural sway. Lumbar tissue creep may also contribute to fatigue level effects. Participants performed 110 ± 34 during low-14, 165 ± 37 during moderate-14 and 245 ± 67 during high-14. The larger number of extensions performed with the higher fatigue levels likely resulted in increasing amounts of creep in the lumbar connective tissue, which may impair trunk control and increase sway as hypothesized earlier. Lumbar extensor fatigue impairs lumbar position sense (Taimela *et al.* 1999) and greater impairment in lumbar position sense with increasing fatigue level may also contribute to increasing sway with increasing fatigue level. Impaired excitation/contraction coupling, perhaps due to decreased calcium ion availability for release from the sarcoplasmic reticulum (Vollestad and Sejersted 1988), has been implicated in the gradual loss of force production capability from intermittent submaximal contractions (Bigland-Ritchie *et al.* 1986). This impairment would presumably progress with increased fatigue levels and affect both extrafusal and intrafusal muscle fibres. This is important because intrafusal muscle fibres modulate the sensitivity of muscle spindles that provide sensory information on muscle velocity and length via Group Ia and II afferents, respectively. Impaired intrafusal muscle fibre contraction capability would reduce the sensitivity of the muscle spindles, reduce joint lumbar position/movement sense, increase trunk movement and increase postural sway. To summarize, increasing fatigue level can compromise multiple aspects of neuromuscular function related to postural control, but the present work does not allow for discriminating which are the most important contributions.

It is of interest to compare the duration of elevated sway measures following lumbar extensor fatigue with the duration of elevated sway measures following other types of muscle fatigue. The present study found that mean and peak sway velocity was higher than unfatigued values until approximately 15 and 9 min of recovery, respectively. This implies, at least in terms of statistical significance, that lumbar extensor fatigue was no longer affecting postural sway after 15 min. It should be noted, however, that visual inspection of these data reveals that mean velocity and peak velocity values remained above unfatigued values for the entire 30 min after the fatigue protocol. Other studies, which have investigated the recovery of postural sway following fatigue of different muscle groups, have shown recovery periods of similar duration. Recovery from neck fatigue (Schieppati *et al.* 2003) was shown to require only 5 min, while recovery from ankle fatigue was shown to take up to 20 min (Yaggie and McGregor 2002). Although direct comparison to other studies is difficult due to differences in fatigue conditions, fatigue times, fatigue level and sway measures employed, the results of the present study are similar to other investigations.

Increased postural sway has been associated with an increase in risk of falling (Overstall *et al.* 1977, Fernie *et al.* 1982, Lichtenstein *et al.* 1988, Maki *et al.* 1994). Although this association has only been established in tests with older adults, and in the absence of data to suggest otherwise, it seems reasonable to suspect this same relationship applies to working-age individuals. Based on this, the effects of fatigue level on sway found here suggest a dose–response relationship between lumbar extensor fatigue and risk of falling, in that higher levels of fatigue may contribute to a higher risk of falling. This relationship has important implications in work/rest cycle scheduling during fatiguing tasks performed at heights. In addition, the effects of fatigue time on sway indicated that fatiguing participants at a lower workload over a longer period of time elicited larger increases in sway compared to fatigue from a higher workload over a shorter period of time. This has important implications in applying laboratory-based results (which typically involve relatively high workloads over a short period of time) to the workplace (which typically involves lower workloads over a longer period of time). The results from the present study suggest that laboratory-based studies using relatively high workloads may be underestimating the effects of fatigue on sway in the workplace.

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