Eur J Appl Physiol (2004) 93: 183–189
DOI 10.1007/s00421-004-1195-1

ORIGINAL ARTICLE

B. S. Davidson · M. L. Madigan · M. A. Nussbaum

Effects of lumbar extensor fatigue and fatigue rate on postural sway

Accepted: 28 June 2004 / Published online: 28 July 2004

Abstract Falls from heights resulting from a loss of balance are a major concern in the occupational setting. Previous studies have documented a deleterious effect of lower extremity fatigue on balance. The purpose of this study was to investigate the effect of lumbar extensor fatigue on balance during quiet standing. Additionally, the effects of fatigue rate on balance and balance recovery rate were assessed. Eight center-of-pressure-based measures of postural sway were collected from 13 participants, both before and after a protocol that fatigued the lumbar extensors to 60% of their unfatigued maximum voluntary exertion force. In addition, postural sway was measured for 30 min after the fatiguing protocol, at 5-min intervals, to quantify balance recovery rate during recovery from fatigue. Two different fatigue rates were achieved by fatiguing participants over either 10 min or 90 min. Results show an increase up to 58% in time-domain postural sway measures with lumbar extensor fatigue, but no change in frequency-domain measures. Fatigue rate did not affect the magnitude of these postural sway increases, nor did it affect the rate of balance recovery following fatigue. Statistical power for the latter result, however, was low. These results show that lumbar extensor fatigue increases postural sway and may contribute to fall-from-height accidents.

B. S. Davidson · M. L. Madigan (✉)
Department of Engineering Science and Mechanics, Virginia Polytechnic Institute and State University, Mail Code 0219, Blacksburg, VA 24061, USA
E-mail: mlmadigan@vt.edu
Fax: +1-540-2314574

M. A. Nussbaum
Grado Department of Industrial and Systems Engineering, Virginia Polytechnic Institute and State University, 250 Durham Hall (0118), Blacksburg, VA 24061, USA

M. L. Madigan · M. A. Nussbaum
Virginia Tech–Wake Forest University School of Biomedical Engineering & Sciences, Blacksburg, Virginia, USA

Keywords Balance · Falls · Fatigue · Postural sway · Spine

Introduction

Falls from heights (FFH) were the fourth leading cause of occupational death in the United States between 1980 and 1994 (NIOSH 2000). During this time period, over 8,000 FFH occurred at an average of about 1.5 deaths per day. Although these numbers were large, they were likely underestimates of actual values since roughly one fifth of work-related deaths are not identified on death certificates, which formed the basis for these statistics. The occupation of roofer is particularly hazardous. Compared to the average worker, roofers are about six times more likely to sustain a fatal occupational injury (Ruser 1995). Even if nonfatal, falls from roofs cause thousands of severe injuries each year that result in substantial medical costs (Gillen et al. 1997; BLS 1998).

In a recent review, Hsiao and Simeonov (2001) reported that the most commonly mentioned cause of falls from roofs was a loss of balance. Balance is a complex, multifaceted construct that is well-known but difficult to quantify. For the purpose of this manuscript, balance will be operationally defined to be equivalent to (or measurable by) postural sway. A logical first step to reduce the number of these falls is to identify factors that contribute to a loss of balance. One factor that has been shown to degrade balance (i.e. increase postural sway) is localized muscle fatigue. This is important because workers frequently engage in fatiguing tasks while working at heights (Hsiao and Simeonov 2001). Studies have reported a degradation of balance due to fatigue in the ankle musculature (Johnston et al. 1998; Vuillerme et al. 2002; Yaggie and McGregor 2002; Caron 2003; Vuillerme and Nougier 2003), fatigue due to repetitive lifting (Sparto et al. 1997), and cardiovascular and lower extremity fatigue from running and cycling (Lepers et al. 1997; Nardone et al. 1997; Gauchard et al. 2002). In addition, studies have reported a degradation of balance with localized shoulder fatigue from prolonged overhead work (Nussbaum 2003), and localized neck fatigue from resistance exercises (Schieppati et al. 2003). These latter two findings are of particular interest because fatigue was induced in muscle groups that are not thought to play a major role in the control of upright balance. Lumbar extensor fatigue may also adversely affect balance, and is of particular importance because it is a common manifestation of many occupational tasks. Therefore, the first objective of this study was to investigate the effect of lumbar extensor fatigue on balance. It was hypothesized that localized fatigue of the lumbar extensors would degrade balance during quiet standing.

When designing a study to investigate the effect of fatigue on balance, researchers must decide upon the rate at which fatigue will be induced. Most studies found in the literature that have investigated the effect of fatigue on balance induced fatigue at a relatively high rate over a short (≤ 10 min) period of time (Sparto et al. 1997; Johnston et al. 1998; Vuillerme et al. 2002; Yaggie and McGregor 2002; Schieppati et al. 2003). In the workplace, however, fatigue may be induced at a lower rate over a long period of time. While fatigue has been shown to degrade balance, it is not known whether fatigue rate affects the loss and recovery rate of balance. Determining this is important for future experiments involving fatigue and balance, and may aid in the development of interventions to mitigate the effect of fatigue on balance. Therefore, the second objective of this study was to investigate the effect of fatigue rate on: (1) the change of balance measures following lumbar extensor fatigue and (2) the rate of balance recovery from fatigue. It was hypothesized that lumbar extensor fatigue rate would not affect the magnitude of any balance degradation, but that fatigue rate would affect the rate of balance recovery following fatigue. Specifically, a lower fatigue rate will be associated with a longer balance recovery, as suggested by Kawabata et al. (2000).

Methods

Thirteen physically active males (20–22 years of age) participated in the experiment. Mean (SD) participant height and weight was 175.8 (7.0) cm and 78.1 (11.6) 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.

Participants completed two experimental sessions that were separated by 1–2 weeks. Each session consisted of four main stages: warm-up, unfatigued balance measurement, fatiguing protocol, and fatigued balance measurement. During both sessions, the back extensor muscles were fatigued to 60% of their unfatigued isometric maximum voluntary exertion (MVE) force. The difference between the sessions was the rate of fatigue (high vs low) controlled by the duration of fatiguing exercises (10 min vs 90 min). The presentation order of fatigue rates was counterbalanced so that half of the participants were initially fatigued at a high rate, while the other half were initially fatigued at a low rate.

Participants warmed up by performing two cycles of the following three activities: jogging at 2.0 km·h^{-1} on a treadmill for 2.5 min, lumbar stretching, and five back extensions. Following the warm-up, unfatigued MVE force of the lumbar extensors was measured (Fig. 1). Participants were positioned on a 45° Roman chair (New York Barbell, Elmira, N.Y.), attached to a load cell (Cooper, Warrenton, Va.) at the mid-sternum via a modified construction harness, and instructed to extend at the back as hard as possible. Participants performed two isometric MVEs separated by 1 min of rest, and the maximum force between the two MVEs was recorded as the unfatigued MVE force.

Next, an unfatigued balance measurement was collected. Participants were instructed to remain as still as possible while standing on a force platform without shoes, with eyes closed, feet together, and arms resting at their side. Each collection lasted 30 s, which has been shown to be sufficient for reliable postural sway measures (Le Clair and Riach 1996; Carpenter et al. 2001).

The fatiguing protocol consisted of multiple sets of back extensions performed on a 45° Roman chair. Investigators attempted to fatigue participants such that their MVE force decreased linearly over the duration of the fatiguing protocol and achieved the desired fatigue level (60% unfatigued MVE) using high and low fatigue rates corresponding to 10-min and 90-min fatiguing protocols, respectively. To accomplish this, participants performed one set of back extensions every minute of the fatiguing protocol, and an isometric back extension MVE every 2 min or 6 min for the high or low fatigue rate, respectively. The number of repetitions in each set was systematically adjusted, based upon a comparison of the measured MVE force to the target force at that time, using an algorithm developed during pilot testing of six participants (Fig. 2). If participants were not at or below 60% of their unfatigued MVE force at the end of the fatiguing protocol, 2 min were added to the exercise period with additional repetitions added according to

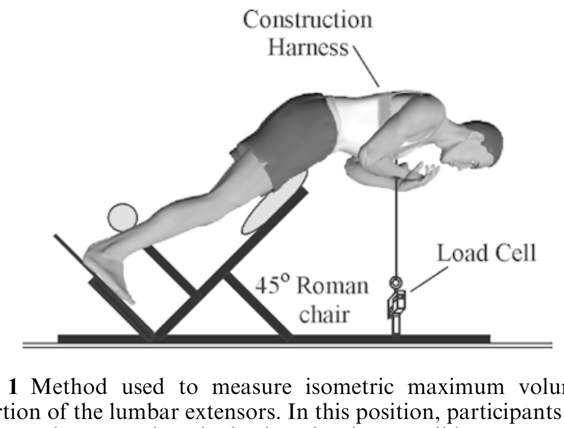


Fig. 1 Method used to measure isometric maximum voluntary exertion of the lumbar extensors. In this position, participants were instructed to extend at the back as hard as possible

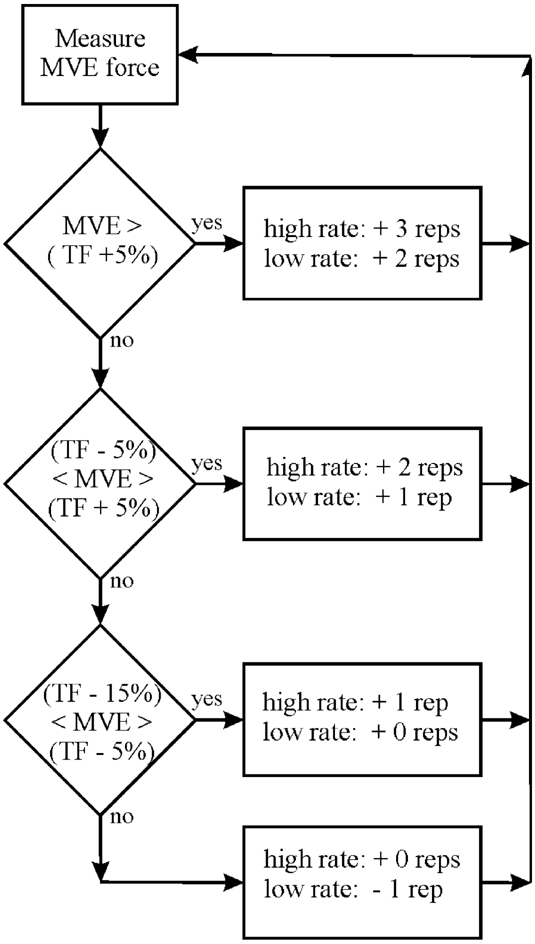


Fig. 2 Algorithm for adjustment of repetitions based upon measured maximum voluntary exertion (*MVE*) force during fatiguing protocols. In each diamond, measured MVE force was compared with the pre-calculated target force (*TF*) for that time. In each rectangle, the number of repetitions added to or subtracted from the current number is shown

the same algorithm. This process of adding 2 min continued until the exerted extension force was below 60% of the unfatigued MVE. Representative MVE measurements and repetition numbers during a low fatigue rate protocol are shown in Fig. 3. Prior to performing the back extensions, participants were instructed to move through approximately 60° range of motion from 0° back extension to maximum flexion possible. A digital metronome set at 30 beats/min^{-1} was used to ensure all participants performed the extensions at a consistent rate.

Immediately following the fatiguing protocol, a fatigued balance measurement was collected in an identical manner to the unfatigued balance measurement. This measurement was initiated within 10 s of completion of the fatiguing protocol. Additional fatigued balance measurements were collected at 5-min intervals for 30 min following completion of the fatiguing protocol, in order to assess changes in balance during recovery from lumbar extensor fatigue. Thirty minutes of recovery measurement was considered sufficient, based on reports that fatigue effects on postural sway last less than 20 min (Nardone et al. 1997, 1998; Yaggie and McGregor 2002).

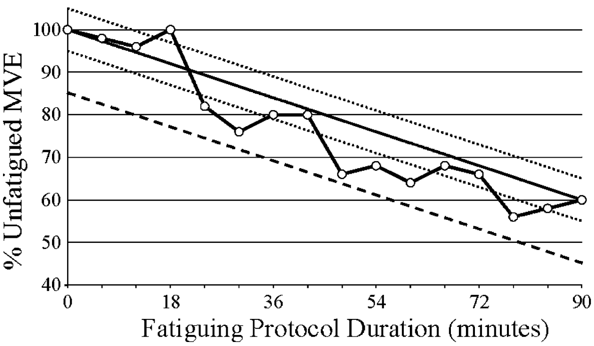
Triaxial ground reaction forces and moments were low-pass filtered with a 500 Hz anti-aliasing hardware filter, amplified, and sampled at 1,000 Hz with a Bertec K20102 type 9090–15 force platform (Bertec, Columbus, Ohio). These data were subsequently low-pass filtered (4th order, 10 Hz low-pass Butterworth filter) and transformed to obtain center-of-pressure (COP) data (Winter 1993). Eight measures of postural sway were calculated from the COP data: mean velocity, peak velocity (Nussbaum 2003), modified ellipse area (Oliveira et al. 1996; Kuo et al. 1998), sway area, mean frequency in the M/L and A/P directions, and median frequency in the M/L and A/P directions (Prieto et al. 1996). Balance recovery rate was quantified by the time constant of an exponential fit to the fatigued balance measurements after normalization, such that the first fatigued balance measurement was equal to 1.

To determine the effects of lumbar extensor fatigue and fatigue rate on postural sway, a two-way repeated measures multivariate analysis of variance (MANOVA) was used initially. MANOVA determined which factors or interactions had significant effects on the dependent variables as a whole. This global assessment was necessary because it was not clear which measures would be most sensitive to fatigue effects. The independent variables for this analysis were fatigue level (unfatigued or fatigued) and fatigue rate (high or low). The dependent variables were the postural sway measures. Because time and frequency domain COP measures may have different sensitivities, a separate MANOVA was performed on each. A significant main effect was followed by separate two-way repeated measures analysis of variance (ANOVA) for each dependent variable using fatigue level and fatigue rate as independent variables.

To determine the effect of fatigue rate on balance recovery rate, a one-way repeated measures MANOVA was initially used. The independent variable for this analysis was fatigue rate (high or low), and the dependent variables were the time constants of the exponential fits to the fatigued postural sway measures. A significant MANOVA was followed by repeated measures ANOVA for each dependent variable. All dependent variables were visually inspected for normality. One participant was excluded from the analysis because his unfatigued balance measurement during the high fatigue rate protocol was judged to be an outlier (e.g. modified ellipse area was >7 standard deviations from the mean of remaining participants). A significance level of $P \leq 0.05$ was used for all statistical tests.

Results

The fatiguing protocol was successful in fatiguing the lumbar extensors to a consistent fatigue level at two different fatigue rates. Participants were fatigued to an



Time	% MVE	reps/min	Time	% MVE	reps/min
0	100	3	48	66	10
6	98	4	54	68	10
12	96	5	60	64	11
18	100	7	66	68	11
24	82	7	72	66	12
30	76	7	78	56	12
36	80	9	84	58	13
42	80	10	90	60	–

Fig. 3 Representative MVE forces and number of set repetitions during a low fatigue rate fatiguing protocol. The *left* side illustrates the target fatigue rate (*solid, straight line*) and three other lines to help specify the number of repetitions performed in each set of the fatiguing protocol (Fig. 2). These lines include the target fatigue rate ±5% (*dotted lines*), and the target fatigue rate −15% (*dashed line*). Actual MVE force measurements collected every 6 min are shown by *solid line with open circles*. The *right* side illustrates the number of repetitions performed each set as adjusted every 6 min using the algorithm shown in Fig. 2

MVE level of 54.5 (6.2)% [mean (SD)] with no significant difference in this level between high and low rate fatiguing protocols ($P=0.208$). The mean (SD) fatigue rates for the high and low rate fatiguing protocols were 4.20 (0.56)% and 0.52 (0.08)% MVE min^{-1}, respectively.

Effect of lumbar extensor fatigue and fatigue rate on postural sway

The general trend in the data indicates an increase in postural sway with lumbar extensor fatigue, and a roughly exponential recovery over the 30 min following the fatiguing protocol (Fig. 4). Similar trends were seen when using high and low fatigue rates. The initial MANOVA performed on the time-domain postural sway measures revealed a significant effect of fatigue ($P=0.021$), no effect of fatigue rate ($P=0.309$), and no interaction between fatigue and fatigue rate ($P=0.943$). Subsequent ANOVAs found that fatigue increased all time-domain postural sway measures except for peak velocity (Table 1). These increases ranged from 29% (mean velocity) to 58% (sway area). MANOVA performed on the frequency-domain measures revealed no effect of fatigue ($P=0.331$), no effect of fatigue rate ($P=0.205$), and no interaction between fatigue and fatigue rate ($P=0.596$). Thus, no subsequent ANOVAs were performed on the frequency-domain measures.

Effect of fatigue rate on postural sway recovery rate

Balance recovery rates were calculated using only the three time-domain postural sway measures that exhibited significant increases with fatigue: mean velocity, modified ellipse area, and sway area. The mean recovery rate for each measurement was negative, indicating a decrease in postural sway during recovery. However, the MANOVA performed on these measures revealed no significant effect of fatigue rate on recovery rate ($P=0.422$). Thus, no subsequent ANOVAs were performed.

Discussion

The first objective of this study was to investigate the effect of lumbar extensor fatigue on balance. A question arose concerning the most appropriate fatigue rate to use when fatiguing participants. Therefore, the second

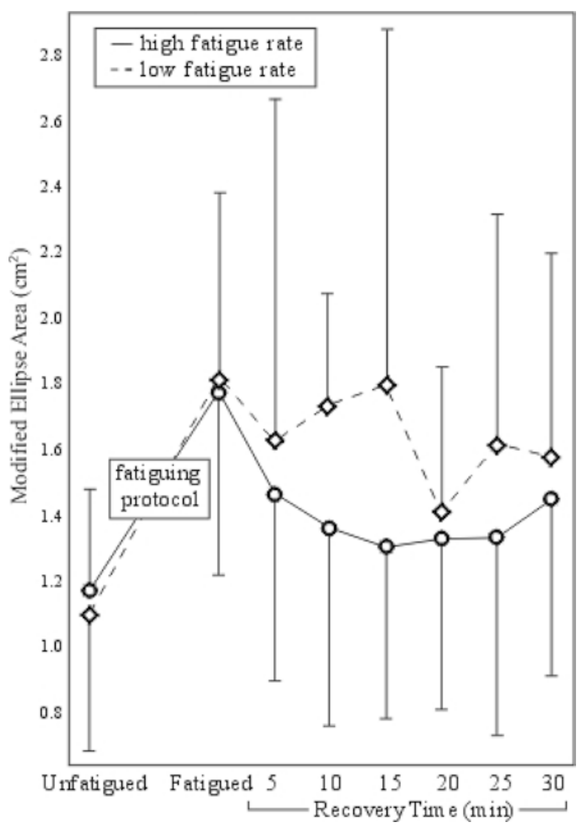


Fig. 4 Mean (SD) time course of modified ellipse area during experimentation for high and low fatigue rates. Measurements were made before fatiguing protocol (unfatigued), just after the fatiguing protocol (fatigued), and at 5-min increments during recovery from lumbar extensor fatigue. Note: the *y*-axis does not start at zero

Table 1 Mean (SD) values of unfatigued and fatigued postural sway measures. Data are pooled across fatigue times due to a lack of fatigue rate effect

Measure	Unfatigued	Fatigued	% Change
Mean velocity (mm·s^{-1})	21.2 (5.0)	27.3 (5.8)	28.9 *
Peak velocity (mm·s^{-1})	155.7 (97.9)	156.1 (44.2)	0.2
Modified ellipse area (cm^2)	1.12 (0.43)	1.77 (0.53)	57.1 *
Sway area (cm^2)	0.53 (0.19)	0.83 (0.27)	57.9 *
ML Mean frequency (Hz)	0.44 (0.15)	0.43 (0.11)	−2.6
AP Mean frequency (Hz)	0.33 (0.11)	0.30 (0.11)	−8.7
ML Median frequency (Hz)	0.27 (0.11)	0.28 (0.11)	3.7
AP Median frequency (Hz)	0.18 (0.09)	0.17 (0.08)	−2.1

*$P = 0.001$

objective was to investigate the effect of fatigue rate on the magnitude of any balance degradation from lumbar extensor fatigue. The effect of fatigue rate on balance recovery was also investigated. Our results indicate: (1) muscle fatigue of the lumbar extensors increased postural sway, (2) fatiguing participants to a consistent fatigue level using two different fatigue rates did not affect the magnitude of the postural sway increase, and (3) fatigue rate did not affect balance recovery rate. It should be noted that an increase in sway is not necessarily an indicator of poorer balance. However, its use as a surrogate measure of balance is common throughout the literature, and there is at least some evidence that risk of falls is related to sway (Lichtenstein et al. 1988, 1989).

Upon review of the published literature on postural sway related to fatigue, a wide range of quantities was found for the stabilogram measurements of interest. In comparison, the results from the present study fell within the range of reported results in the time domain (Derave et al. 1998; Karlsson and Frykberg 2000; Vuillerme et al. 2002; Nussbaum 2003; Vuillerme and Nougier 2003) and frequency domain (Corbeil et al. 2003).

The increase in postural sway that was found with lumbar extensor fatigue implies impaired postural control. Other studies have shown an increase in postural sway with lower extremity fatigue, but it was not intuitive that lumbar extensor fatigue would increase postural sway because these muscles are not typically considered to have a large role in standing balance control. It remains to be explained how lumbar extensor fatigue impaired postural control in this study. Three sensory systems are involved in balance control: visual, vestibular, and proprioceptive (somatosensory) (Mirka and Black 1990). The visual system could not contribute to the measured increase in postural sway because participants had their eyes closed during postural sway measurements. The vestibular system was not likely affected by neuromuscular fatigue. Therefore, proprioception was the most likely system involved. One potential explanation to the increase in postural sway found in this study is a decrease in muscle proprioceptive acuity with fatigue. Numerous studies have concluded that muscle fatigue has an adverse effect on joint proprioception (Christensen 1976; Skinner et al. 1986; Lattanzio et al. 1997; Björklund et al. 2000). In fact, Taimela et al. (1999) reported an impaired ability to sense a change in lumbar position following lumbar fatigue. If proprioceptive feedback of torso position is impaired by lumbar extensor fatigue, larger angular movements at the lumbar joint can be expected before they are detected. These movements would lead to greater displacement of the whole-body center-of-mass (COM) during quiet standing, demanding a concomitant increase in COP displacement to maintain the COM within the base of support. This was consistent with our data in that we observed an increase in COP area which indicates larger sway amplitude. In addition, trunk and hip proprioceptive input may provide the triggers for many balance corrections (Allum et al. 1995; Bloem et al. 2002). Impairment of these proprioceptive signals can delay stabilizing muscle activation, and would readily explain the documented increase in postural sway following lumbar fatigue.

At least two other potential explanations to the increase in postural sway following lumbar fatigue exist. First, reduced muscular force due to fatigue could potentially contribute to the observed increase in sway. However, we feel this is unlikely because of minimal lumbar extensor activity during quiet standing (Floyd and Silver 1955) and growing support for the inverted pendulum model of quiet standing (Winter et al. 1998; Karlsson and Frykberg 2000; Gage et al. 2004) which implies that the lumbar extensors have a minor role in postural control. Second, smoothness of muscle force output has been shown to decrease with fatigue (Ng et al. 2003). This decreased stability of muscle force may have contributed to more erratic control of the trunk, and consequently increased postural sway.

Another potential explanation is an increase in postural sway due to an increase in respiration rate which has been documented in several previous studies (Hunter and Kearney 1981; Jeong 1991; Bouisset and Duchene 1994; Sakellari and Bronstein 1997). We can state qualitatively that subjects experienced an increase in respiration rate, but respiration was not measured quantitatively. To address this issue, a small control experiment was performed on three subjects to: (1) quantify the increase in respiration rate due to our fatiguing protocol, and (2) determine if an identical increase in respiration rate in the absence of lumbar extensor fatigue increases postural sway. We found that respiration rate increased 6–12 breaths·min^{-1} after our fatiguing protocol. On a separate day, subjects returned to the laboratory to collect postural sway data during three trials of quiet standing while breathing at their normal respiration rate, and breathing at their increased respiration rate measured after the fatiguing protocol. Mean postural sway measures collected at increased respiration rate were lower in all three subjects compared to measures collected at normal respiration rate. This suggests that the increase in respiration rate in our study resulting from the fatiguing protocol did not contribute significantly to the measured increase in postural sway. A similar conclusion was made by Nardone et al. (1997).

Our results indicate that fatigue rate did not affect the increase in postural sway with lumbar fatigue. The statistical powers of these tests were $>70\%$ for two of the four time-domain measures and three of the four frequency-domain measures. This indicates that we can have a moderately high level of confidence that there was in fact no difference between fatigue rates. Our results also indicate that fatigue rate did not affect balance recovery rate. The statistical power of this test, however, was low ($<10\%$). The power analysis revealed that we likely would have found a difference between balance recovery rates if the effect size was approximately six times larger than the effect size found. To improve statistical power, future studies should employ three strategies: (1) include more subjects, (2) use more consistent measures of postural sway, and/or (3) impose a wider range of fatigue rates. Although statistical tests revealed no significance between fatigue rates, Fig. 4 illustrates a general trend that subjects recovered more quickly after the high fatigue rate protocol. Also notable is that the increase in COP measures did not return to the unfatigued values within the 30-min period as reported by Nardone et al. (1997, 1998) and Yaggie and McGregor (2002). This was most likely due to the differing levels of fatigue and fatiguing methods, or also due to differences in the muscles investigated.

There were several limitations to our study. MVE measurements during the experiment were not corrected for the weight of the upper body. As a result, the actual MVE levels achieved were lower than the 60% MVE target. A post hoc analysis of the measured MVE forces corrected for upper body mass using an anthropometric model (de Leva 1996) revealed that subjects were actually fatigued to 49–74% of their unfatigued MVE. However, a paired *t*-test found no significant difference in fatigued MVE across fatigue rates ($P=0.198$), which suggests that comparisons between the two fatigue rates are still valid. A second limitation of our study was the subject pool. The study used a sample of convenience of only young healthy males and caution should be used when extrapolating these results to other populations. A third potential limitation of our study was participant motivation level. As with most fatigue and balance studies, both MVE and balance measurements assumed participants consistently provide their best effort throughout all data collections.

In conclusion, muscle fatigue of the lumbar extensors increased postural sway. Our results also indicated that fatigue rate did not affect postural sway, suggesting that future studies investigating the effect of fatigue on balance need not employ fatigue rates typically encountered in the workplace for results to be applicable to the workplace. Fatigue rate also did not affect balance recovery rate, but the statistical power for this test was low. With further study, these results could potentially contribute to the development of occupational interventions aimed at mitigating the effect of lumbar extensor fatigue on balance, and ultimately to a reduction in the number of FFH accidents and deaths.

Acknowledgements The authors would like to acknowledge the financial support for this research provided by the Jeffress Memorial Trust, Richmond, Va., and also thank Matthew Runion for his work in the laboratory. The above-mentioned experimentation wholly complied with all current laws regarding the research and testing of human participants in both the United States of America and the Commonwealth of Virginia.

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