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Postural sway and joint kinematics during quiet standing are affected by lumbar extensor fatigue

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Abstract

The purpose of this study was to investigate changes in postural sway and strategy elicited by lumbar extensor muscle fatigue. Specifically, changes in center of mass (COM), center of pressure (COP), and joint kinematics during quiet standing were determined, as well as selected cross correlations between these variables that are indicative of movement strategy. Twelve healthy male participants stood quietly both before and after exercises that fatigued the lumbar extensors. Whole-body movement and ground reaction force data were recorded and used to calculate mean body posture and variability of COM, COP, and joint kinematics during quiet standing. Three main findings emerged. First, participants adopted a slight forward lean post-fatigue as evidenced by an anterior shift of the COM and COP. Second, post-fatigue increases in joint angle variability were observed at multiple joints including joints distal to the fatigued musculature. Despite these increases, anterior–posterior (AP) ankle angle correlated well with AP COM position, suggesting the body still behaved similar to an inverted pendulum. Third, global measures of sway based on COM and COP were not necessarily indicative of changes in individual joint kinematics. Thus, in trying to advance our understanding of how localized fatigue affects movement patterns and the postural control system, it appears that joint kinematics and/or multivariate measures of postural sway are necessary.

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1. Introduction

A growing number of studies have reported an increase in postural sway during quiet standing with localized muscle fatigue. These studies investigated fatigue at the ankle (Caron, 2003; Corbeil, Blouin, Begin, Nougier, & Teasdale, 2003; Gribble & Hertel, 2004a, 2004b; Lundin, Feuerbach, & Grabiner, 1993; Ochsendorf, Mattacola, & Arnold, 2000; Vuillerme, Danion, Forestier, & Nougier, 2002; Vuillerme & Nougier, 2003; Vuillerme, Nougier, & Prieur, 2001; Yaggie & McGregor, 2002), low back (Davidson, Madigan, & Nussbaum, 2004), shoulder (Nussbaum, 2003), and neck (Gosselin, Rassoulian, & Brown, 2004; Schieppati, Nardone, & Schmid, 2003). Results from these studies show an increase in sway using measures of center of mass (COM) or center of pressure (COP) trajectory, which is thought to indicate a change in postural control, postural stability, or risk of falling (Maki, Holliday, & Topper, 1991). While these measures of sway are without question important in terms of assessing postural stability and control, they can be limited in their ability to discern different postural strategies and movement patterns (Barin, 1992; Kuo, Speers, Peterka, & Horak, 1998). It is necessary to describe postural sway, and the changes associated with fatigue, using additional measures more sensitive to subtle changes in movement throughout the body in order to advance our understanding of the mechanisms behind the increases in sway with fatigue.

To our knowledge, no studies have reported the effects of localized muscle fatigue on lower extremity joint kinematics during quiet standing. As such, it is not clear what specific changes in body movement occur that cause the reported increase in COP- or COM-based measures of postural sway. Are the effects local to the fatigue site or do they involve movement at multiple joints? Is there any evidence of a change in postural strategy that may indicate altered postural control? Answering these questions will expand our understanding of postural control, and may help in the development of interventions designed to mitigate the effects of fatigue on balance. A previous study from our laboratory reported an increase in COP-based measures of postural sway with lumbar extensor fatigue (Davidson et al., 2004). In an effort to answer the previously stated questions, the main objective of this study was to identify changes in postural sway and strategy during quiet standing elicited by lumbar extensor fatigue. Specifically, changes in COM, COP, and joint kinematics during quiet standing were investigated, along with selected cross correlations between these variables that are indicative of movement strategy.

2. Methods

Twelve physically active males (20–22 years of age) participated in the experiment. Mean $\pm$ standard deviation (SD) participant height and mass were 173.7 ± 6.4 cm and 70.2 ± 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. This study was performed in accordance with ethical standards established in the 1964 Declaration of Helsinki. Participants attended three experimental sessions with at least one week between consecutive sessions. During each session, body position and COP data were collected during quiet standing both before and after a lumbar extensor fatiguing protocol. Participants were fatigued to one of three fatigue levels during each session, although fatigue level was not used as an independent variable because it was the focus of a separate study. The fatigue levels were 86%, 73%, and 60% of the unfatigued isometric maximum voluntary contraction (MVC) torque of the lumbar extensors.

At the start of each session, and after a brief warm-up routine, the unfatigued isometric MVC torque of the lumbar extensors was measured at the level of L3. Participants were positioned on a 45° Roman chair, attached to a load cell (Cooper Instruments and Systems, Warrenton, VA) at the mid-sternum via a modified construction harness, and instructed to extend at the back as hard as possible (Fig. 1). Using the load cell data and an estimation of head, arms, and trunk mass and COM position to correct for gravitational force on the upper body (de Leva, 1996), the corresponding torque at the "back joint" (approximately L3) was estimated for all MVCs. Participants performed three isometric MVCs separated by 1 min of rest; the largest of the three was recorded as the unfatigued MVC value. Next, one unfatigued quiet standing trial was performed. 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. This duration has been shown to be sufficient for reliable postural sway measures (Carpenter, Frank, Winter, & Peysar, 2001; Le Clair & Riach, 1996).

The fatigue protocol has been described in detail elsewhere (Davidson et al., 2004), and will only be summarized here. The fatiguing protocol consisted of multiple sets of back extensions performed on the 45° Roman chair. Investigators attempted to fatigue participants such that their lumbar extensor MVC torque decreased linearly over the duration of the fatiguing protocol and achieved the desired fatigue level over 14 min. To accomplish this, participants performed one set of back extensions every minute of the fatiguing protocol, and an isometric lumbar extensor MVC every 2 min. The number of repetitions in each set was systematically adjusted based upon a comparison of the measured MVC torque to

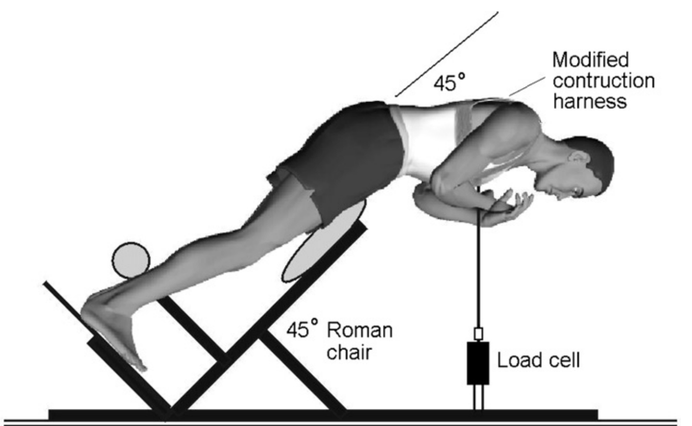

Fig. 1. Participant positioned on the 45° Roman chair to perform an isometric MVC of the lumbar extensors. In this position, the lumbar flexion angle was approximately 45°.

the target torque at that time (Davidson et al., 2004). Prior to performing the back extensions, participants were instructed to move through approximately 60° range of motion from maximum flexion to 0° back extension. A digital metronome set at 30 min^{-1} was used to ensure all participants performed the extensions at a consistent rate. Immediately following the fatiguing protocol, one fatigued balance trial was performed in an identical manner as the unfatigued balance trial. This trial was initiated within 10 s of completing the fatiguing protocol.

During each trial, ground reaction forces and moments were obtained using a Bertec K20102 type 9090-15 force platform (Bertec Corp., Columbus, OH). 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 4th order Butterworth), downsampled to 50 Hz, and transformed into COP data (Winter, 2005). Body segment positions were sampled at 50 Hz using a Vicon 460 motion analysis system (Vicon Motion Systems Inc., Lake Forest, CA) and low-pass filtered at 7 Hz (zero-phase-lag 4th order Butterworth). Markers were placed bilaterally over the acromion, iliac crest, greater trochanter, lateral femoral epicondyle, lateral malleolus, calcaneus, and head of the 5th metatarsal. To calculate joint kinematics and whole-body COM, the marker position data were averaged across the left and right sides of the body and used to create a five segment model of the body including the feet, shanks, thighs, pelvis, and trunk (endpoints defined by the iliac crest and shoulder). Using these five segments, joint angles were calculated for the ankle, knee, hip, and back joints (the back joint was defined as the angle between the pelvis and trunk segments) in the anterior–posterior (AP) and medial–lateral (ML) planes. Whole-body COM position was determined in the AP and ML planes with published mass and inertial characteristics of the body segments (de Leva, 1996). The mean and SD of COM position, COM velocity, COP position, COP velocity, joint angular position, and joint angular velocity were calculated in AP and ML planes for each quiet standing trial.

Posture was described using the following dependent variables: (1) mean COM and COP position in AP plane; (2) mean joint angles in AP plane. Postural sway was described using the following dependent variables: (1) SD of COM and COP position in AP and ML planes; (2) SD of ankle, knee, hip, and back angles in AP; (3) SD of ankle, hip, and back in ML; (4) SD of ankle, knee, hip, and back angular velocity in AP; (5) SD of ankle, hip, and back angular velocity in ML. Cross correlations between the time series of selected variables were also performed in an attempt to quantify AP postural strategy in terms of the so-called ankle strategy and hip strategy. Peak values of the resulting cross correlation function were used for statistical analyses. The cross correlations were performed with MATLAB V7.0 (The MathWorks, Inc., Natick, MA) using the entire 30 s of data and evaluated between: (1) AP ankle angle and AP COM position; (2) AP hip angle and AP COM position; (3) AP ankle angle and AP hip angle. A two-way repeated measures ANOVA was used to determine the statistical significance of the effect of fatigue on the dependent variables. For dependent variables of joint angles and joint angular velocities, independent variables were joint (ankle, knee, hip, or back) and fatigue (unfatigued or fatigued). For dependent variables of COM and COP position and velocity, independent variables were sway metric (COM or COP) and fatigue (unfatigued or fatigued). Separate analyses were performed for AP and ML planes. Pairwise comparisons were performed using Tukey's HSD. Several variables required a $\log_{10}$ transformation to achieve an approximately normal distribution prior to statistical analysis. In these cases, variables were back-transformed prior to reporting. Paired t-tests were used to investigate the effect of fatigue on peak values of cross correlation functions. All statistical analyses were performed using JMP IN (SAS Institute Inc., Cary, NC) with a significance level of 0.05.

3. Results

Several differences were found between movement of the COM and COP, as well as between the ankle, knee, hip, and back joints. The SD of COP position was slightly higher than the SD of COM position in both AP and ML planes, $F(1,127) = 14.96$, $p < .01$, $f = .34$; $F(1,122) = 7.13$, $p < .01$, $f = .24$, respectively. Similarly, the SD of COP velocity was slightly higher than the SD of COM velocity in the AP and ML planes, $F(1,127) = 764.39$, $p < .01$, $f = 2.45$; $F(1,122) = 1039.71$, $p < .01$, $f = 2.92$, respectively. These findings were not surprising given that the COP must oscillate more than the COM to keep it within the base of support. The SD of AP joint angles and joint angular velocities increased in a distal to proximal order with the largest values at the hip and back joints (Fig. 2). The SD of ML joint angles, however, was largest at the ankle followed by the low back and hip. The SD of ML joint angular velocities increased in a distal to proximal order, as in the AP plane.

Several characteristics of posture and sway changed with fatigue. Posture changed in that participants adopted a slight forward lean with fatigue as evident by a 0.7 ± 1.7 cm anterior shift in mean COM position, $F(1,59) = 9.50$, $p < .01$, $f = .40$, and a 1.5 ± 1.5 cm anterior shift in mean COP position, $F(1,57) = 34.23$, $p < .01$, $f = .77$. This lean was due to a 1.0 ± 2.6 degree increase in ankle dorsiflexion, $F(1,59) = 5.59$, $p = .02$, $f = .31$. No other AP joint angles changed with fatigue, $F(1,146) = .04$, $p = .85$, $f = .02$. Fatigue had different effects on postural sway in the AP and ML planes (Fig. 3). In the AP plane, fatigue did not affect SD of COM or COP position, $F(1,127) = .09$, $p = .77$, $f = .03$. In the ML plane, SD of COM and COP position both decreased, $F(1,122) = 27.79$, $p < .01$, $f = .48$. Together, these results indicate no change in COM/COP excursions in the AP plane with fatigue, and smaller excursions in the ML plane. In contrast to these differential effects, SD of COM and COP velocities increased in both the AP and ML planes, $F(1,127) = 19.28$, $p < .01$, $f = .39$; $F(1,122) = 10.62$, $p < .01$, $f = .30$, respectively.

Fatigue affected joint kinematics at all joints investigated (Fig. 4). In the AP plane, fatigue increased the SD of all joint angles and joint angular velocities, $F(1,267) = 42.08$, $p < .01$, $f = .40$; $F(1,268) = 57.05$, $p < .01$, $f = .46$, respectively. The trend of SD of joint angular velocities increasing in a distal to proximal order was exaggerated with fatigue not only by increasing the SD over all joints, but with larger increases at the more proximal joints. Specifically, increases at both the back and hip were larger than increases at the ankle and knee. In the ML plane, SD of ankle angle decreased with fatigue and SD of back angle increased with fatigue, $F(1,53) = 5.98$, $p = .02$, $f = .36$; $F(1,53) = 6.79$, $p = .01$, $f = .36$, respectively. Fatigue also increased the SD of joint angular velocities in the ML plane, $F(1,185) = 10.90$, $p < .01$, $f = .24$.

Cross correlations revealed statistically significant changes with fatigue (Table 1). Prior to fatigue, AP ankle angle exhibited a strong positive correlation with AP COM position, and AP hip angle exhibited little correlation with AP COM position. Poor correlation between AP ankle angle and AP hip angle indicated little coordination between these two movements. These results suggest a strong reliance on the ankle strategy for AP postural control. Fatigue changed the sign of the peak values of the cross correlation functions (positive to negative) between AP hip angle and AP COM position as well as between AP hip angle and AP ankle angle. This suggests a fatigue-induced shift toward more anti-phase

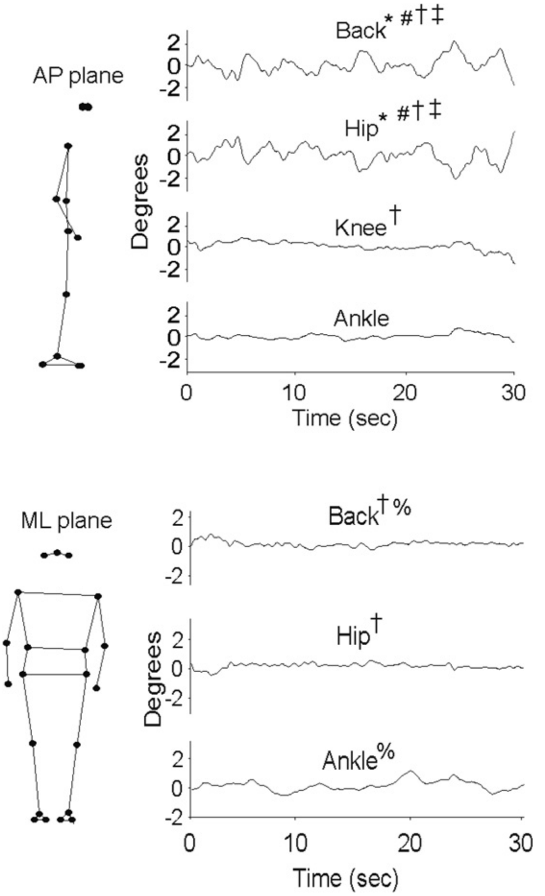

Fig. 2. Sample joint kinematics during quiet standing when unfatigued. In the AP plane, SD of joint angles increased in a distal to proximal order. In the ML plane, SD of joint angles was largest at the ankle followed by the low back and hip. * indicates SD of joint angle greater than that of ankle ($p < .05$). # indicates SD of joint angle greater than that of knee ($p < .05$). † indicates SD of joint velocity greater than that of ankle ($p < .05$). ‡ indicates SD of joint velocity greater than that of knee ($p < .05$). % indicates SD of joint angle greater than that of hip ($p < .05$).

movement between the legs and trunk (as typically seen with the hip strategy), but these correlations remained low. In addition, the correlation between ankle angle and AP COM position remained high, suggesting that the ankle strategy remained the dominant strategy post-fatigue.

4. Discussion

The main objective of this study was to identify changes in body movements during quiet standing elicited by lumbar extensor muscle fatigue. Three main findings emerged. First, participants adopted a slight forward lean when fatigued. Second, changes in sway involved increases in joint angle variability at multiple joints, including joints distal to the fatigued musculature. Despite these increases, AP ankle angle correlated well with AP

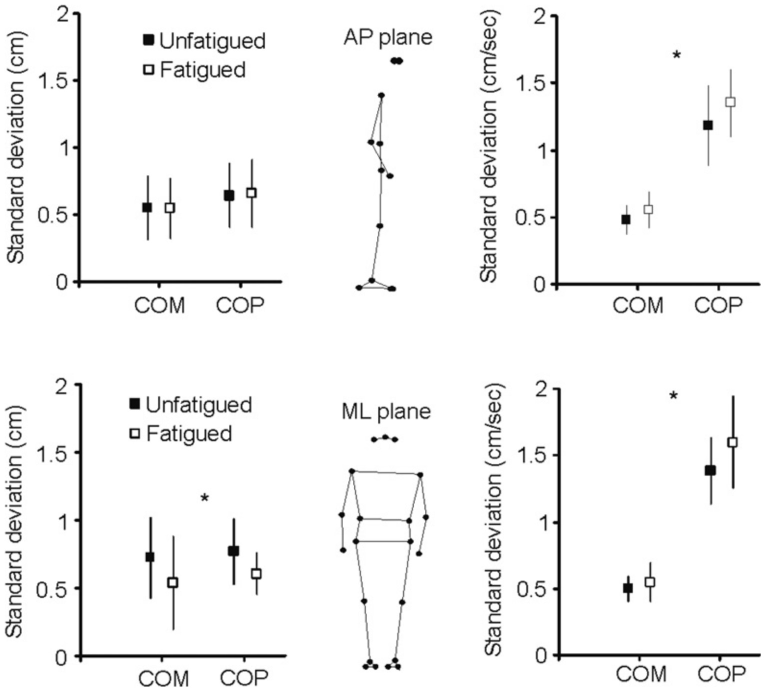

Fig. 3. Effects of fatigue on COM and COP kinematics. Two plots on left show SD of COM and COP position while two plots on right show SD of COM and COP velocity. Two upper plots show AP plane kinematics and two lower plots show ML plane kinematics. * indicates significant effect of fatigue ($p < .01$) for both COM and COP measures.

COM position, suggesting the body still behaved similar to an inverted pendulum with an ankle strategy. Third, global measures of sway based on COM and COP were not necessarily indicative of changes in individual joint kinematics.

Many studies investigating the effects of localized fatigue on postural sway have found simultaneous increases in both COM/COP displacement and velocity measures, and at least two studies have reported an increase in COP velocity and no change in COP displacement with fatigue as reported here (Caron, 2003; Corbeil et al., 2003). Perhaps the seemingly more consistent finding of increased COM/COP velocity with localized muscle fatigue is indicative of the changes in postural control with fatigue. Moreover, velocity-related measures have been reported to separate stable postural control from reduced stability better than displacement-related sway measures (Maurer & Peterka, 2005; Prieto, Myklebust, Hoffmann, Lovett, & Myklebust, 1996). Using an inverted pendulum model of the body and proportional–integral–differential (PID) controller, Maurer and Peterka (2005) reported that COP mean velocity was positively correlated with ankle stiffness, afferent feedback time delay, and system noise. Thus, the increase in COP velocity in the present study may be due to fatigue-induced increases in these same three system parameters. These changes are also consistent with other results from the present study. First, the slight forward lean with fatigue would necessitate increased plantar flexor activity and likely ankle stiffness (Brown & Frank, 1997). Second, fatigue has been associated with slowed conduction velocity of afferent signals (Nardone, Tarantola, Giordano, & Schieppati, 1997) which

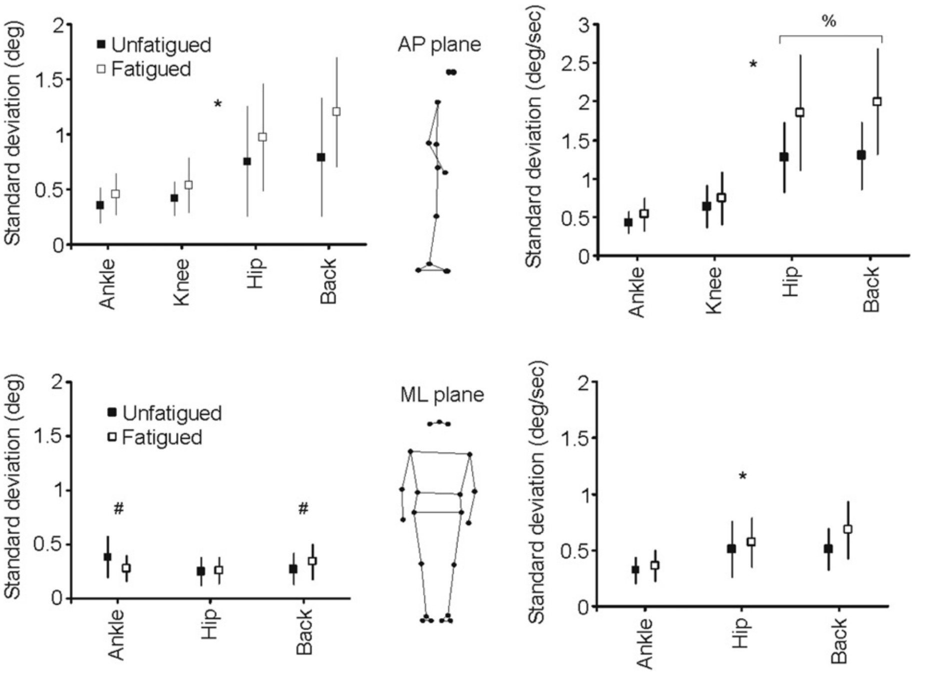

Fig. 4. Effects of fatigue on joint kinematics. Two plots on left show SD of joint angles while two plots on right show SD of joint angular velocities. Two upper plots include AP plane kinematics and two lower plots include ML plane kinematics. * indicates significant effect of fatigue ($p < .01$) for joints shown. # indicates significant effect of fatigue ($p < .05$). % indicates increases at hip and back were larger than increases at ankle and knee ($p < .05$).

Table 1
Mean ± SD of maximum of cross correlation function

Variables cross correlated		Unfatigued	Fatigued	
AP ankle angle	AP COM position	0.80 ± 0.18	0.79 ± 0.17	*
AP hip angle	AP COM position	0.17 ± 0.46	−0.13 ± 0.45	**
AP ankle angle	AP hip angle	0.15 ± 0.48	−0.19 ± 0.50	†

Notes: Ankle and hip angles were positive for flexion (dorsiflexion), and COM position was positive for anterior movement. Thus, correlation between AP hip angle and AP COM position would be +1.0 for pure hip strategy (no ankle movement). Correlation between AP ankle angle and AP hip angle would be −1.0 for equivalent anti-phase movement of legs and trunk involving ankle plantar flexion and hip flexion, or ankle dorsiflexion and hip extension.

* $t(32) = .08, p = .94, d = .05$.

** $t(35) = -2.68, p = .01, d = .69$.

† $t(35) = -3.55, p < .01, d = .82$.

would increase time delay. Third, increased hip/back movement may be viewed as an increase in system noise in light of the fact that the Maurer and Peterka model was based on a single segment inverted pendulum.

Our joint kinematics closely agreed with Gatev, Thomas, Kepple, and Hallett (1999), who investigated the effects of feet width and vision on lower extremity joint kinematics during quiet standing. This agreement includes a qualitative assessment of greater variability in joint angles and angular velocities at proximal joints compared to distal joint in AP plane, as well as a quantitative comparison of SD of sway variables between the studies. Regarding the forward lean reported here after lumbar extensor fatigue, Lundin et al. (1993) similarly reported a forward lean during unilateral stance after dorsiflexor/plantar flexor fatigue. In their study, sway and forward lean were recorded using a specialized balance system that reported "center of balance" values, which are related to center of pressure, but the difference between them precluded direct comparison with the forward lean found here. We are unaware of any other studies that found a forward lean during quiet standing with fatigue. However, it is unclear how many studies actually investigated such an effect since close monitoring of foot position on the forceplate, which is necessary to recognize a forward lean, is not necessary when collecting stabilograms.

The slight forward lean adopted by participants may represent a strategic change in posture that provides a beneficial effect on controlling sway when fatigued. The slight forward lean would necessitate an increase in ankle plantar flexor muscle activity, which would result in an increase in ankle stiffness. Even though increased ankle stiffness requires more 'neural effort', it may lessen the demands on the postural control system by reducing the reliance on sensory feedback. It may also improve the sensitivity of muscle spindles in the plantar flexors to changes in muscle length and velocity due to the increased gamma-motoneuron drive. These potential benefits are important because localized muscle fatigue has been linked with losses of proprioceptive acuity both at the site of fatigue (Lattanzio, Petrella, Sproule, & Fowler, 1997; Taimela, Kankaanpaa, & Luoto, 1999) and at other sites not directly affected by fatigue (Pline, Madigan, Nussbaum, & Grange, 2005; Sharpe & Miles, 1993). It is interesting to note that increasing the ankle stiffness in an inverted pendulum model (Winter, Patla, Prince, Ishac, & Gielo-Perczak, 1998) would cause it to oscillate at a higher frequency (i.e. increase the natural frequency). Our results are consistent with participants oscillating at a higher frequency based on the increase in the SD of AP COM and COP velocities.

One may question whether the changes in sway were due to fatigue *per se*, or the slight forward lean. Two arguments suggest that fatigue was the main contributor. First, low Pearson product moment correlations between mean COM position and SD of both sway and joint kinematics indicate a weak relationship between these measures. Second, a follow-up analysis was performed by repeating our statistical analysis on a subset of participants whose change in mean COM position with fatigue was less than the overall mean of 7.7 mm. This subset of participants showed a mean −6.2 mm (posterior) shift in mean COM position, and all trends in global measures of sway and joint kinematics were identical to the trends reported for all participants. For these reasons, we do not attribute the changes in sway solely to the slight forward lean.

Our results show an increase in AP ankle, knee, hip, and low back angle/angular velocity variability with increases at the hip and low back being at least twice as much as at the ankle. In regards to the so-called 'ankle strategy' and 'hip strategy' that have been used to characterize AP movements during recovery from a postural perturbation (Nashner & McCollum, 1985), these changes may be interpreted as a shift toward hip strategy during quiet standing. We would like to suggest otherwise. We feel the increased movement at the hip was not due to a purposeful change in postural strategy by the postural control system. Rather, we propose that the increased movement at the hip during quiet standing was due to disruptions in proprioception and/or neuromuscular performance associated with fatigue at the fatigue site.

The dynamics of quiet standing can be simplified using a single inverted pendulum without excessive loss of external validity (Gage, Winter, Frank, & Adkin, 2004). A more accurate, albeit more complex, model of quiet standing would involve a double inverted pendulum due to the nontrivial angular movement at the hip and back. The upper segment of the double pendulum could represent the head–arms–trunk, pivot at the hip joint, and be controlled in the AP plane with the hip extensors and flexors. This segment would have a mass of approximately 68% body mass and a COM located 37% of the torso height superior from the hip joint (Winter, 2005). Because of this, it would be susceptible to the same instability that induces spontaneous sway about the ankles when using a single inverted pendulum. Given this, it is also not surprising that there is spontaneous movement at the hip during quiet standing to stabilize the upper body, especially when one considers this upper segment is supported by a lower body segment that is continuously moving. The movement of the upper segment upon the hip joint is the basis behind studies investigating seated postural sway (Bennett, Abel, & Granata, 2004). Lumbar extensor fatigue has been shown to impair lumbar proprioceptive acuity (Taimela et al., 1999). Such an impairment would likely result in larger joint angle/velocity variability since the ability to detect a change in joint angle or velocity would require larger changes. This is consistent with our results at the hip and back in both the AP and ML planes. Moreover, if larger hip/back movements were interpreted as a shift toward hip strategy, it would also be expected that coordination between ankle and hip angles would be improved. The low correlation between ankle and hip angles in both unfatigued and fatigue conditions found here suggests poor coordination between the two joints.

Our results also indicated that global measures of sway based on COM and COP are not necessarily indicative of changes in individual joint kinematics. Two hypothetical scenarios can help illustrate how this can occur. In the first scenario, localized muscle fatigue elicits an increase in AP COM and COP movement due to an increase in ankle movement. The knee, hip, and low back remain rigid similar to an inverted pendulum. Here, the global measures of sway based on COM and COP would be highly correlated with ankle kinematics. In the second scenario, localized muscle fatigue elicits no change in AP COM and COP movement, but an increase in ankle and hip AP movement. This could theoretically occur if the movement at the ankle and hip were anti-phase and, in essence, cancelled out any AP movement of the COM (e.g. simultaneous ankle plantar flexion and hip flexion). Here, the global measures of sway based on COM and COP would not be correlated with individual joint kinematics. The results of the present study appear to be consistent with the second scenario. Thus, in trying to advance our understanding of how localized fatigue affects movement patterns and postural control during quiet standing, it appears that univariate measures of sway are inadequate. Instead, joint kinematics or multivariate measures of sway (Kuo et al., 1998) are necessary.

In conclusion, lumbar extensor fatigue elicited a slight forward lean during quiet standing, and increased lower extremity joint angle and angular velocity variability. The largest increases in joint angle and angular velocity were at the hip and back, which provide similar function in terms of controlling the torso, and were located close to the fatigue site. These increases were attributed to fatigue-induced neuromuscular deficits at this site. Global measures of postural sway were not necessarily indicative of localized changes in sway. Additional studies are needed to investigate changes in joint kinematics with localized muscle fatigue at other sites in order to advance our understanding of the effects of fatigue on the postural control system.

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References

Barin, K. (1992). Dynamic posturography: Analysis of error in force plate measurements of postural sway. *IEEE Engineering in Medicine and Biology Magazine, 11*, 52–56.

Bennett, B. C., Abel, M. F., & Granata, K. P. (2004). Seated postural control in adolescents with idiopathic scoliosis. *Spine, 29*, E449–E454.

Brown, L. A., & Frank, J. S. (1997). Postural compensations to the potential consequences of stability: Kinematics. *Gait & Posture, 6*, 89–97.

Caron, O. (2003). Effects of local fatigue of the lower limbs on postural control and postural stability in standing posture. *Neuroscience Letters, 340*, 83–86.

Carpenter, M. G., Frank, J. S., Winter, D. A., & Peysar, G. W. (2001). Sampling duration effects on centre of pressure summary measures. *Gait & Posture, 13*, 35–40.

Corbeil, P., Blouin, J. S., Begin, F., Nougier, V., & Teasdale, N. (2003). Perturbation of the postural control system induced by muscular fatigue. *Gait & Posture, 18*, 92–100.

Davidson, B. S., Madigan, M. L., & Nussbaum, M. A. (2004). Effects of lumbar extensor fatigue and fatigue rate on postural sway. *European Journal of Applied Physiology, 93*, 183–189.

de Leva, P. (1996). Adjustments to Zatsiorsky–Seluyanov's segment inertia parameters. *Journal of Biomechanics, 29*, 1223–1230.

Gage, W. H., Winter, D. A., Frank, J. S., & Adkin, A. L. (2004). Kinematic and kinetic validity of the inverted pendulum model in quiet standing. *Gait & Posture, 19*, 124–132.

Gatev, P., Thomas, S., Kepple, T., & Hallett, M. (1999). Feedforward ankle strategy of balance during quiet stance in adults. *Journal of Physiology, 514*(Pt 3), 915–928.

Gosselin, G., Rassoulian, H., & Brown, I. (2004). Effects of neck extensor muscles fatigue on balance. *Clinical Biomechanics (Bristol, Avon), 19*, 473–479.

Gribble, P. A., & Hertel, J. (2004a). Effect of hip and ankle muscle fatigue on unipedal postural control. *Journal of Electromyography and Kinesiology, 14*, 641–646.

Gribble, P. A., & Hertel, J. (2004b). Effect of lower-extremity muscle fatigue on postural control. *Archives of Physical Medicine and Rehabilitation, 85*, 589–592.

Kuo, A. D., Speers, R. A., Peterka, R. J., & Horak, F. B. (1998). Effect of altered sensory conditions on multivariate descriptors of human postural sway. *Experimental Brain Research, 122*, 185–195.

Lattanzio, P. J., Petrella, R. J., Sproule, J. R., & Fowler, P. J. (1997). Effects of fatigue on knee proprioception. *Clinical Journal of Sport Medicine, 7*, 22–27.

Le Clair, K., & Riach, C. (1996). Postural stability measures: what to measure and for how long. *Clinical Biomechanics (Bristol, Avon), 11*, 176–178.

Lundin, T. M., Feuerbach, J. W., & Grabiner, M. D. (1993). Effect of plantarflexor and dorsiflexor fatigue on unilateral postural control. *Journal of Applied Biomechanics, 9*, 191–201.

Maki, B. E., Holliday, P. J., & Topper, A. K. (1991). Fear of falling and postural performance in the elderly. *Journal of Gerontology, 46*, M123–M131.

Maurer, C., & Peterka, R. J. (2005). A new interpretation of spontaneous sway measures based on a simple model of human postural control. *Journal of Neurophysiology, 93*, 189–200.

Nardone, A., Tarantola, J., Giordano, A., & Schieppati, M. (1997). Fatigue effects on body balance. *Electromyography and Motor Control – Electroencephalography and Clinical Neurophysiology, 105*, 309–320.

Nashner, L. M., & McCollum, G. (1985). The organization of human postural movements: a formal basis and experimental synthesis. *Behaviorial and Brain Sciences, 8*, 135–172.

Nussbaum, M. A. (2003). Postural stability is compromised by fatiguing overhead work. *AIHA Journal (Fairfax, VA), 64*, 56–61.

Ochsendorf, D. T., Mattacola, C. G., & Arnold, B. L. (2000). Effect of orthotics on postural sway after fatigue of the plantar flexors and dorsiflexors. *Journal of Athletic Training, 35*, 26–30.

Pline, K. M., Madigan, M. L., Nussbaum, M. A., & Grange, R. W. (2005). Lumbar extensor fatigue and circumferential ankle pressure impair ankle joint motion sense. *Neuroscience Letters, 390*, 9–14.

Prieto, T. E., Myklebust, J. B., Hoffmann, R. G., Lovett, E. G., & Myklebust, B. M. (1996). Measures of postural steadiness: differences between healthy young and elderly adults. *IEEE Transactions on Biomedical Engineering, 43*, 956–966.

Schieppati, M., Nardone, A., & Schmid, M. (2003). Neck muscle fatigue affects postural control in man. *Neuroscience, 121*, 277–285.

Sharpe, M. H., & Miles, T. S. (1993). Position sense at the elbow after fatiguing contractions. *Experimental Brain Research, 94*, 179–182.

Taimela, S., Kankaanpaa, M., & Luoto, S. (1999). The effect of lumbar fatigue on the ability to sense a change in lumbar position. A controlled study. *Spine, 24*, 1322–1327.

Vuillerme, N., Danion, F., Forestier, N., & Nougier, V. (2002). Postural sway under muscle vibration and muscle fatigue in humans. *Neuroscience Letters, 333*, 131–135.

Vuillerme, N., & Nougier, V. (2003). Effect of light finger touch on postural sway after lower-limb muscular fatigue. *Archives of Physical Medicine and Rehabilitation, 84*, 1560–1563.

Vuillerme, N., Nougier, V., & Prieur, J. M. (2001). Can vision compensate for a lower limbs muscular fatigue for controlling posture in humans? *Neuroscience Letters, 308*, 103–106.

Winter, D. A. (2005). *Biomechanics and motor control of human movement*. New York, NY: Wiley-Interscience.

Winter, D. A., Patla, A. E., Prince, F., Ishac, M., & Gielo-Perczak, K. (1998). Stiffness control of balance in quiet standing. *Journal of Neurophysiology, 80*, 1211–1221.

Yaggie, J. A., & McGregor, S. J. (2002). Effects of isokinetic ankle fatigue on the maintenance of balance and postural limits. *Archives of Physical Medicine and Rehabilitation, 83*, 224–228.