Biomechanical Evaluation of Lumbar Extensor Fatigue Effects on the Postural Control System

BRADLEY STEVEN DAVIDSON

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Michael L. Madigan, Ph.D., Chair

Maury A. Nussbaum, Ph.D.

Kevin P. Granata, Ph.D.

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(ABSTRACT)

Falls from heights are the fourth leading cause of occupational injury and fatality in the United States. In particular, construction workers such as roofers are often exposed to high risk environments. Recent research has reported that a leading cause of falls among workers is a loss of balance. Therefore, in moving towards reducing the number of occupational falls, further investigation of balance and factors that influence postural control is necessary. The effect of neuromuscular fatigue has been addressed by many investigators; however, few studies have examined the effect of localized fatigue in muscles not located in the lower extremities. Because low back fatigue is so prevalent during manual labor, this investigation determined to study the effects of lumbar extensor fatigue on balance. Chapter 1 includes a complete review of current literature addressing the effects of muscular fatigue on measures of balance. Chapter 2 details an initial investigation of lumbar extensor fatigue on center of pressure (COP) based measures of postural sway and examines the effect of fatiguing rate. Chapter 3 examines the effects of different levels of lumbar extensor fatigue and expands on the previous investigation by examining center of mass (COM) movement and incorporating additional measures of postural control. The results of these investigations indicate that lumbar extensor fatigue affects both COP and COM measures of postural sway, and might also lead to an increased reliance on feedforward postural control mechanisms. These findings contribute to understanding of effects of fatigue on balance and may aid the future design of interventions aimed at fall prevention.

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CHAPTER 1

Introduction

Between 1980 and 1989, falls from heights were the fourth leading cause of occupational injuries and fatalities in the United States (NIOSH 2000). More recently, of the 6660 fatalities recorded in the construction industry from 1990 to 1999, 2353 of these (35.3%) were the result of a fall (Derr et al. 2001). These falls occurred most often from buildings, and falls from roofs accounted for the greatest number of fatal falls. The occupation of roofer is a particularly high risk job.

Hsaio and Simeonov (2001) have indicated that, in roofers, the most common cause of falls reported is a loss of balance. Because balance plays a key role in fall prevention, it is imperative that possible causes of balance impairment in the workplace be thoroughly investigated in order to help reduce the number of falls from heights. Past studies have discovered deleterious effects of muscle fatigue on balance. Because muscle fatigue is common while performing manual labor, balance degradation due to muscle fatigue could significantly contribute to the number of occupational falls. Therefore the main focus of this research was the influence of muscle fatigue on the postural control system and balance.

Background

Balance is a term which is frequently used in everyday conversation and also by clinicians. Every individual has some qualitative understanding of balance or loss of balance. Despite its widespread use, there is no universally accepted definition of balance (Ekdahl et al. 1989; Pollock et al. 2000). As such, many approaches have been used to quantify balance. Investigators have used the duration of a participant to remain in a certain stance, ability to control a moving platform, various measures of center of pressure (COP) and center of mass (COM) trajectories, as well as a myriad of other commercial devices to assess balance and changes in balance.

A common biomechanical description of balance is the body's ability to maintain its center of mass within its base of support (Kreighbaum and Barthels 1990; Hall 1991; Massion 1994; Pollock et al. 2000). COM movement (also referred to as sway) is controlled by movement of the center of pressure primarily by the ankle and hip musculature during quiet standing. Because a human body has approximately two-thirds of its mass located two-thirds its height above the ground, the body is inherently unstable and requires continuous adjustment of the COP (Winter 1993). Movement of the COP, although not identical, is generally in phase with movement of the COM. This quality, along with its relative ease of collection, has made measures of the COP trajectory an attractive method of quantitative assessment of postural sway and balance. Changes in these measures have been associated with increased falls in the elderly (Lichtenstein et al. 1989; Riach and Starkes 1994b) and may also indicate risk of falling outside of this population.

The following paragraphs reviewing the current literature on the effects of fatigue on measures of postural sway and are organized into four sections. The first section outlines the earliest studies reporting the effects of fatigue on balance. Next, more recent studies are addressed beginning with non-localized fatigue due to cardiovascular exercise or total body fatiguing movements. In the third section, localized muscle fatigue in the lower extremities is examined. Finally, a review of localized muscle fatigue not located in the lower extremities is presented.

Earliest Reported Studies Investigating the Effects Fatigue on Balance

Although the last decade has presented an increase in the number of studies investigating the effects of fatigue on measures of balance, this topic is not new. As long ago as 1949 the effects of fatigue induced by a physical efficiency test on balance were investigated by Scott and Matthews. Slocum (1953) performed a similar study. A more recent publication (Nielson and Johnson 1973) reported that both studies found improved balance performance following the efficiency test, and Slocum hypothesized that the improvement resulted from a warm-up effect. The first scientific evidence of potential balance impairment due to fatigue was offered by Culhane (1956) in an unpublished Master's thesis. Here, a slight loss in static balance performance is reported following two minutes of cycling; however, the loss was not statistically significant. It was suggested that the exercise was not strenuous enough to produce "genuine fatigue."

The topic of fatigue effects on balance was relatively quiet until 1973, when Nielson and Johnson analyzed the effects of "general fatigue" and "local fatigue" on static balance. Local fatigue was administered through maximum number of one-legged toe raises while general fatigue was administered through maximum number of squat thrusts. Static balance was quantified by the length of time which participants could remain in a one-legged stance. It was found that both heel raises and squat thrusts significantly reduced the length of one-legged standing, but the effects of the squat thrusts were more detrimental.

Three years later, an investigation was performed which compared the fatigue of several different muscle groups on balance as measured with a "dynabalometer" (Miller and Bird 1976). Four muscle groups were fatigued: dorsiflexors; plantarflexors; abdominals; knee and hip flexors and extensors). Twenty participants were randomly assigned to each muscle group and twenty were used as a control group. Only the group which fatigued the knee and hip flexors and extensors with squats demonstrated a significant difference in balance as measured by the "time in balance" on an unstable platform.

Almost fifteen years transpired before the next study pertaining to fatigue effects on balance. During this interlude biomechanics was revolutionized by technological advances and improved methodology. Equipment such as force platforms and motion monitoring systems were developed, and along with vast improvement of computer processing and data collection, the current era of biomechanical analysis arrived.

Studies Investigating the Effects of Cardiovascular/Total Body Fatigue

Several investigations have explored the effects of fatigue induced by cardiovascular or total body fatigue on measures of postural sway. For this purpose, these studies will be categorized as total body fatigue since both cardiovascular and general muscle groups were simultaneously fatigued. For instance, in a study that utilizes up-hill treadmill walking (Nardone et al. 1998) the cardiovascular system was fatigued along with lower body musculature. It is also possible that arm movement while walking induced some amount of shoulder fatigue. The vast majority of these studies reported an increase in sway measures with fatigue. With the exception of two investigations (Derave et al. 1998; Paul et al. 2001), studies inducing fatigue by walking, running (Lepers et al. 1997; Nardone et al. 1997; Nardone et al. 1998), or cycling (Lepers et al. 1997; Gauchard et al. 2002) reported increases in COP measures.

Seliga et al. (1991) first demonstrated an increase in sway measures following sub-maximal aerobic cycling. However, Nardone et al. (1997) reported decreases following cycling and increases following a 25 km run in highly trained athletes. Causes of the increased sway measures observed were speculated as resulting from a failure of energy metabolism and excitation-coupling contraction (Baker et al. 1993) or depression in muscle spindle afferent discharge leading to decreased γ-motoneurone activation (Hagbarth and Macefield 1995). The unexpected decrease following cycling was attributed to "the training effect due to the repetition of the stance trials".

Nardone et al. (1998) examined the time course of sway measures following fatigue induced by up-hill treadmill walking. Fatigued COP data were not collected until 2-3 minutes after the fatiguing exercises because the researchers waited until the "feeling of dizziness" subsided. Sway measures demonstrated only a small increase after fatiguing exercises. Reasons given for only a small increase were 1) that due to eccentric contractions during walking, muscles in the lower extremity are resistant to fatigue and 2) muscles are tonically active at only low levels (Soames and Atha 1981; Schieppati et al. 1994). Fatigue effects on sway measures lasted no longer than 10 to 15 minutes.

Lepers et al. (1997) studied the "equilibrium performance" of well-trained athletes (triathletes and running specialists) following long-distance running. Dynamic posturography was performed before and after a 25 km run on an Equitest platform system. This system allowed performance of a Sensory Organization Test (SOT) which exposed the participant to six different sensory conditions. The system returned an "equilibrium score" as well as a "strategy score". Equilibrium was associated with sway movements while the strategy distinguished between ankle or hip strategies. Results indicated a decreased ability to maintain equilibrium following the fatiguing run, as well as a shift towards a hip strategy when both support surface and visual references were made to be inaccurate. A cycling portion was also included for the triathlete participants where similar results were found. It was hypothesized that the body modifies the integration of sensory information post fatigue and therefore, equilibrium was compromised in dynamic environments.

In an investigation of the combined effects of dehydration and fatigue induced by cycling, Gauchard et al. (2002) subjected participants to VO2 max testing on a cycle ergometer, and endurance exercise at 60% VO2 max with and without hydration. Overall amplitude of the frequency spectrum was quantified by calculating the amplitude spectral density (Patat et al. 1985) of the COP trajectory before and after exercise. Increases in sagittal plane frequency spectrum amplitudes were found in VO2 max testing and exercise without hydration. Measures following VO2 max testing demonstrated the largest change with fatigue.

Paul et al. (2001) and Derave et al. (1998) were two studies in the category of general fatigue which showed no changes in postural sway measures. Paul et al. investigated changes in COP measures after light exercise in patients with and without Chronic Fatigue Syndrome. No changes were measures (2001)possibly due to the low intensity of the cycling exercise. Derave et al. tested the effects of exercise-induced and thermal dehydration on postural sway measures. Fatigue was accomplished by a two-hour cycling protocol. However, the lack of a fatigue effect may be explained by latency of the fatigued balance collection, which was performed twenty minutes after exercise ceased. This is beyond the time period some authors reported that effects of fatigue have subsided (Nardone et al. 1997; Nardone et al. 1998; Yaggie and McGregor 2002).

Johnston et al. (1998) investigated changes in motor control following exercises on an Cybex Kinetron II isokinetic dynamometer (similar to a Stairmaster). Balance was assessed using a commercial device called a KAT which calculated a “balancing index” based upon the angular position of an unstable platform. Balance index score was inversely proportional to ability to balance. Results from unilateral and bilateral static tests demonstrated decrease in ability to balance (higher index). A dynamic motor control test exhibited a higher index, but was not statistically significant.

An investigation of multijoint kinematics during a series of box lifts by Sparto et al. (1997) also recorded COP data before and after a series of box lifts. Ankle, knee, hip, and lumbar muscles were fatigued during the lifting task. These data revealed an increase in COP excursion along with a simultaneous anterior shift following this total body fatigue.

Studies Investigating the Effects of Localized Muscular Fatigue in the Lower Extremities

By far, the largest number of studies investigating the effects of fatigue on postural sway or postural control has involved localized muscle fatigue of muscle groups in the lower extremities, specifically the ankle musculature. Lundin et al. (1993) determined that dorsi-plantarflexor fatigue increased sway parameters in the anteroposterior (AP) and mediolateral (ML) directions during unilateral stance as measured by a Chattecx Balance System. An anterior shift in COP location was also observed which has been demonstrated by other authors following fatigue (Sparto et al. 1997).

Contrary to Lundin et al. (1993) and Nielson and Johnson (1973), Adlerton and Moritz (1996) found no changes after plantarflexor fatigue. One other investigation of the effects of plantarflexor fatigue on postural sway during bilateral stance (Corbeil et al. 2003) demonstrated increased COP mean velocity, mean radius, and median frequency. This study concluded that "fatigue places higher demands on the postural control system by increasing the frequency of actions needed to regulate the upright stance."

Vuillerme et al. (2001; 2002; 2003), while presuming the destabilizing effect of plantarflexor fatigue, has investigated different effects of afferent input on the balance system.

In 2001, Vuilerme et al. determined that the presence of visual cues allowed the body to more quickly compensate for the effects of fatigue. Vuillerme et al. (2002) tested the combined effects of plantarflexor fatigue and muscle vibration on postural sway measures. These two conditions alone cause a deleterious effect on postural sway. However, when muscle vibration was applied following fatigue, there was no additional increase in sway. Two hypotheses were offered to account for this: 1) fatigued muscles are less sensitive to vibration or 2) the CNS relies less on afferent information from fatigued muscles to control postural sway. Vuillerme and Nougier (2003) reported on the effects of light finger touch on postural sway following plantarflexor fatigue with similar results as Vuillerme et al. (2002). They concluded that haptic cues from the finger, which contribute to total proprioceptive feedback, possibly increased following fatigue.

Yaggie (2002) sought to add fatigue of ankle inverters and everters to the treatment of ankle fatigue and postural sway. Increases of non-directional and both AP/ML sway measures were reported. However, because the measures of sway were not clearly defined, definitive interpretation is not possible.

Investigations of ankle dorsiflexor fatigue by Caron (2003; 2004) have explored the relationship between postural control and "postural stability". Stability is defined here as movement of the COM while postural control is quantified by the COP trajectory. Dorsiflexor fatigue was selected for this research because "plantarflexors are rarely involved in quiet stance" (Okada 1973). In particular, these studies sought to first assess COM and COP relationship in the presence of ankle dorsiflexor fatigue (2003), and next to determine if there is interaction effects of local fatigue and vision (2004). In each study, COP measures significantly changed with dorsiflexors fatigue while measures of the COM trajectory did not. Effects in Caron (2004) were more pronounced in the eyes open condition. These results indicate that changes in postural control (mean velocity, frequency) do not necessarily imply a decrease in postural stability. This hypothesis was derived from an earlier investigation which employed a comparative analysis of COP and COM trajectories (Caron et al. 2000).

Instead of focusing on the effects of a single muscle group, Gribble and Hertel have compared the effects of fatiguing different lower body muscles on COP mean velocity. In a study which separately fatigued the ankle, knee, and hip muscles in the sagittal plane, an increase in COP mean velocity was found in each condition (Gribble and Hertel 2004b). Interestingly, the increase in mean velocity was present in both the AP and ML directions, and larger following knee and hip fatigue than after ankle fatigue. In a similar investigation which fatigued the lower extremity joints (ankle, hip) in the frontal plane (Gribble and Hertel 2004a), changes were only found following hip fatigue. Although these studies only examined mean velocity of the COP trajectory, they have provided evidence to suggest that muscular fatigue more central to the body would cause an adaptive change in postural control.

Studies Investigating the Effects of Localized Muscular Fatigue not in the Lower Extremities

All of the studies previously mentioned which involve localized muscle fatigue have focused on the lower extremity musculature. Since lower extremity muscles are commonly associated with the control of upright posture and balance, these changes are somewhat intuitive. Recently, several studies have reported the effect of localized fatigue in muscles not primarily thought to be responsible for balance control.

Nussbaum (2003) investigated the effects of localized shoulder fatigue following overhead work on COP measures of sway. Fatigue was induced by a series of repetitive overhead tapping sessions lasting a total of three hours (or until participants chose to terminate the task). COP data was collected before and after each tapping session. Here, the effect of prolonged fatiguing work on postural sway measures was assessed. Participants who did not complete all of the tapping sessions showed a significantly larger increase in sway measures than those who did finish.

Both Schieppati et al. (2003) and Gosselin et al. (2004) investigated the effects of neck extensor muscle fatigue on COP measures of sway, and arrived at comparable conclusions. Gosselin et al. (2004) recorded COP data while participants stood quietly with closed eyes, and reported increases in displacement and velocity measures overall and in the AP direction. Schieppati et al. (2003) determined that the effects on postural sway were significant only in an eyes closed condition. Neck extensor fatigue is purported to sending abnormal sensory input to the CNS which is overcome by visual information.

Motivation

Falls from heights are a major concern. In order to develop effective interventions to help prevent falls from heights, it is important to identify factors which may contribute to falls from heights. Lumbar extensor fatigue is a common occurrence while performing manual labor, such as in the construction industry, and may contribute to falls from heights. Therefore, the following two chapters report the results of two studies investigating the effects of lumbar extensor fatigue on standing balance:

> The purpose of the first study was to develop an objective, valid, and reliable method for fatiguing the lumbar extensor muscles, and to investigate the effects of

lumbar extensor fatigue and fatiguing rate on COP measures of postural sway during quiet standing.

The purpose of the second study was to further the investigation of lumbar extensor fatigue on postural sway and postural control. More specifically, the effect of lumbar extensor fatigue on directional measures of postural sway, postural steadiness, and stiffness measures derived from the inverted pendulum model of quiet standing were investigated.

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CHAPTER 2

Effects of lumbar extensor fatigue and fatigue rate on postural sway

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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 (COP) based measures of postural sway were collected from thirteen participants, both before and after a fatiguing protocol that fatigued the lumbar extensors to 60% of their unfatigued maximum voluntary exertion force. In addition, postural sway was measured for thirty minutes after the fatiguing protocol, at five minute intervals, to quantify balance recovery rate during recovery from fatigue. Two different fatigue rates were achieved by fatiguing participants over either 10 or 90 minutes. Results indicated a 30-50% increase 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 showed that lumbar extensor fatigue increased postural sway and may contribute to fall from height accidents.

Introduction

Falls from heights (FFH) were the fourth leading cause of occupational deaths 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 since a change in postural sway is indicative of a change in the balance system. 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 minutes) 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 measurements. 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 minutes vs. 90 minutes). 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 $km \cdot hr^{-1}$ on a treadmill for 2½ minutes, lumbar stretching, and five back extensions. Following the warm-up, unfatigued MVE force of the lumbar extensors was measured using the setup shown in Figure 1. Participants were positioned on a 45° Roman chair (New York Barbell, Elmira, NY), 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. Participants performed two isometric MVEs separated by one minute of rest, and the maximum force between the two MVEs was recorded as the unfatigued MVE force.

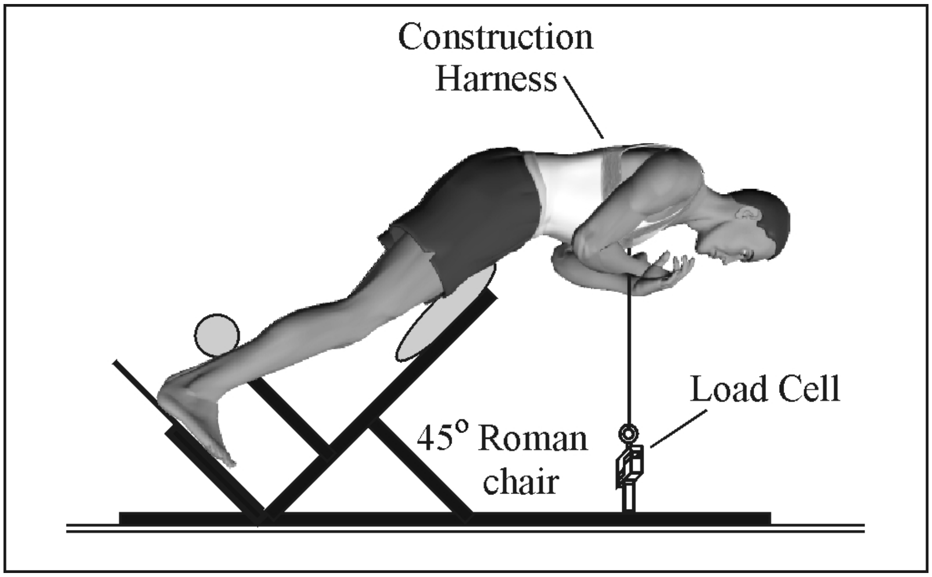


Figure 1: Method used to measure isometric MVEs of the lumbar extensors. In this position, participants were instructed to extend at the back as hard as possible.

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 thirty seconds, which has been shown to be sufficient for reliable postural sway measures (Le Clair and Riach 1996; Carpenter et al. 2001b).

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 one of two fatigue rates (high and low fatigue rates correspond to 10 minute and 90 minute 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 two or six minutes for the high and low fatiguing rates, 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 (Figure 2).

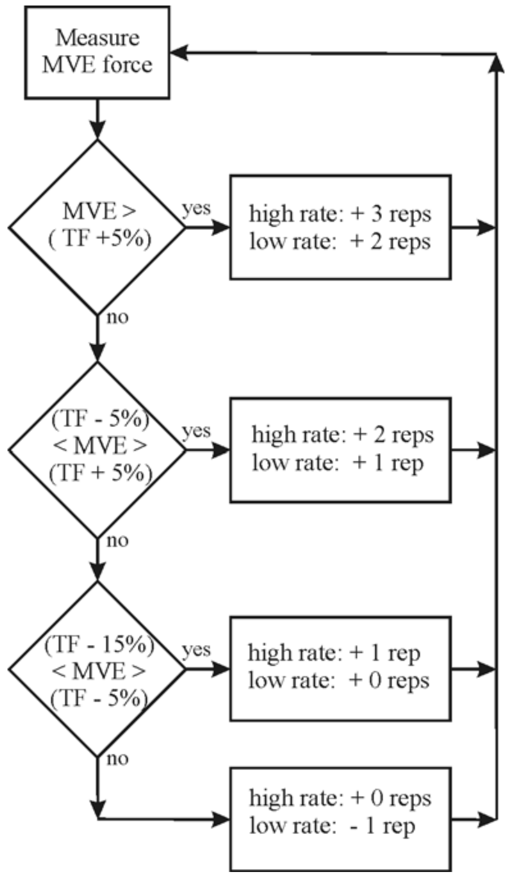
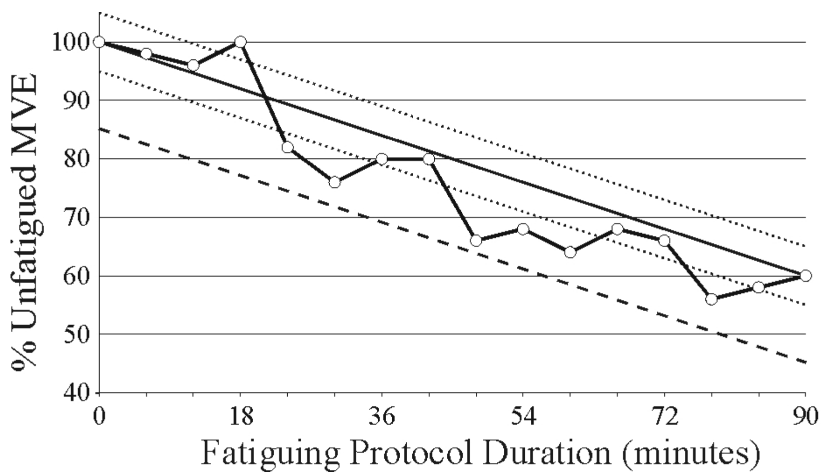


Figure 2: Algorithm for adjustment of repetitions based upon measured MVE force during fatiguing protocols. In each diamond, measured MVE force was compared with the pre-calculated target force (TF) for that time. In each rectangle, the number of repetitions added to or subtracted from the current number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

If participants were not at or below 60% of their unfatigued MVE force at the end of the fatiguing protocol, two minutes were added to the exercise period with additional repetitions added according to the same algorithm. This process of adding two minutes 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 Figure 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 min^{-1} was used to ensure all participants performed the extensions at a consistent rate. Before commencing MVEs or fatiguing exercises, the height of the Roman chair was adjusted to be at least one inch higher than the participant's anterior superior spine of the ilium. This was done to eliminate pelvic motion and further localize the lumbar extensor fatigue.



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	–

Figure 3: Representative maximum voluntary exertion (MVE) forces and number of set repetitions during a low fatigue rate fatiguing protocol. The left side illustrates the target fatigue rate along with ±5% and -15% guidelines. MVE force measurements collected every six minutes are shown by open circles. The right side illustrates the number of repetitions performed each minute as adjusted every 6th minute using the algorithm shown in Figure 2.

Immediately following the fatiguing protocol, a fatigued balance measurement was collected in an identical manner as the unfatigued balance measurement. This measurement was initiated within ten seconds of the completion of the fatiguing protocol. Additional fatigued balance measurements were collected at five minute intervals for thirty minutes following completion of the fatiguing protocol in order to assess changes in balance during recovery from lumbar extensor fatigue. Thirty minutes of recovery measurements was considered sufficient based on reports that fatigue effects on postural sway last less than twenty minutes (Nardone et al. 1997; Nardone et al. 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 1000 Hz with a Bertec K20102 type 9090-15 force platform (Bertec Corp., Columbus, OH). These data were subsequently low-pass filtered (4^{th} order, 10 Hz low-pass Butterworth filter) and transformed to obtain COP data (Winter 1993). Eight measures of postural sway were calculated from the COP data: mean velocity, peak velocity (Nussbaum 2003), modified ellipse area (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 one.

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 separate analyses were performed. This prevented the frequency-domain measures from "diluting" any significance of the time-domain measures. 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 paired *t*-tests 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 a mean (SD) MVE level of 54.5 (6.2) %, 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$\cdot$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 minutes following the fatiguing protocol (Figure 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.

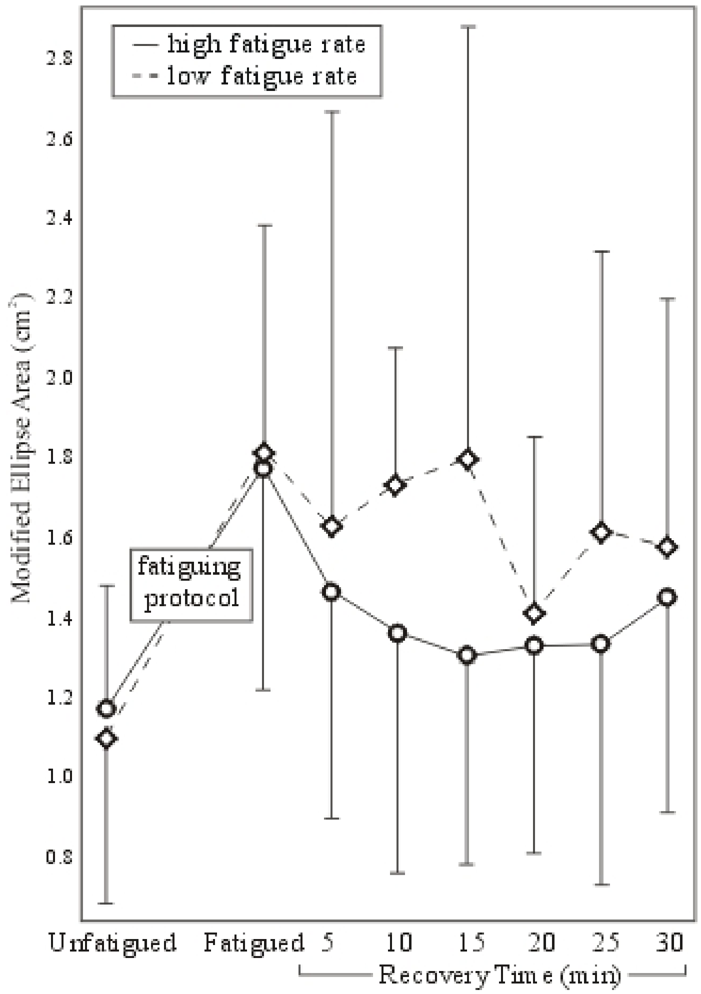


Figure 4: Mean (SD) time course of modified ellipse area during experimentation for high and low fatigue rates. Measurements were made before fatiguing protocol (unfatigued), just after the fatiguing protocol (fatigued), and at five minute increments during recovery from lumbar extensor fatigue. Note: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

Effect of fatigue rate on postural sway and 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. Despite these results, a visual inspection of the measurement trends revealed a different course of recovery for differing fatigue rates.

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 ($mm \cdot s^{-1}$)	21.2 (5.0)	27.3 (5.8)	28.9 *
Peak Velocity ($mm \cdot s^{-1}$)	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 Freq. (Hz)	0.44 (0.15)	0.43 (0.11)	-2.6
AP Mean Freq. (Hz)	0.33 (0.11)	0.30 (0.11)	-8.7
ML Median Freq. (Hz)	0.27 (0.11)	0.28 (0.11)	3.7
AP Median Freq. (Hz)	0.18 (0.09)	0.17 (0.08)	-2.1

* $p = 0.001$

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 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.

Upon review of the published postural sway literature 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) systems (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, the proprioceptive system 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. Additionally, studies by Allum et al. (1995) and Bloem et al. (2002) have indicated that trunk and hip proprioceptive input may provide the triggers for most balance corrections. Impairment of the This would easily explain the increase in postural sway following lumbar fatigue

At the same time, we saw no change in COP mean or median frequencies. This implies that after fatigue, subjects swayed with larger amplitude, but at the same frequency, resulting in an increase in mean velocity (as found).

At least two other potential explanations to the increase in postural sway following lumbar fatigue exist. 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. Post testing was performed including three participants in order to address this concern. Each participants underwent a high fatiguing rate and respiration rate was measured before and after the fatiguing exercises. In each instance, the respiration rate increased (6-12 breaths$\cdot$min^{-1}). The following week, three rested stabilograms were collected from the participants while they breathed normally, and then while breathing at the higher rate recorded after the fatiguing exercises. Breathing rate was controlled using a digital metronome and COP was collected and processed in an identical manner as descrived above. Sway measures shown to be significant (modified ellipse, mean velocity, and sway area) were calculated for each stabilogram and plotted for comparison. For each subject, the measures decreased in the presence of a higher rate of respiration. This leads to the conclusion, as with (Nardone et al. 1997), that an increase in respiration rate played a very small, if any at all, in the increase in postural sway measures.

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, Figure 4 presents interesting trends in recovery, and merits further investigation. Also notable is that the increase in COP measures does not return to the unfatigued values within the thirty minute period as in the previous research earlier cited. This was most likely due to the differing levels of fatigue and fatiguing methods, or also due to differences in the muscles investigated. Future experiments will be conducted in order to more adequately address the effects of fatigue rate on recovery of sway.

There were several limitations to this 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 this study was the subject pool. This 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 this 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. This suggests that lumbar extensor fatigue could potentially contribute to a loss of balance while working at heights. 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. Despite these shortcomings, this experiment is the first documentation of the effects of lumbar extensor fatigue on balance and represents an initial step towards understanding these phenomena. 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.

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CHAPTER 3

Lumbar extensor fatigue affects postural sway and postural control during quiet standing

Abstract

The purpose of this investigation was to explore the changes on the postural control system following lumbar extensor fatigue. In addition, effects following differing fatiguing levels and fatiguing times were consider. Twelve participants visited the laboratory four times, each separated by one week. In each session, participant's lumbar extensors were fatigued to a desired percentage of maximum voluntary contraction over either 14 or 90 minutes. Measures of postural sway, postural steadiness, and postural control were collected before and after lumbar extensor fatigue. Results indicated that lumbar extensor fatigue had differential effects on sway and sway control in AP and ML directions. Increases in ankle stiffness suggested a shift toward greater reliance on feedforward control of balance compared to feedback control. Fatiguing participants to different levels and over different fatiguing times did not affect the magnitude of postural sway changes associated with fatigue.

Introduction

The ability to balance oneself in an upright stance is vital to perform most daily activities. Even a momentary loss of this ability when exposed to heights could lead to a fall causing serious injury and or death. In an effort to prevent falls and their resulting morbidity and mortality, it is important to understand factors that can affect balance. To this end, numerous studies have investigated the effect of various factors on postural sway during quiet stance, which is commonly used as a surrogate measure of balance. Some of these factors include age

(Hasselkus and Shambes 1975; Baloh et al. 1994; Laughton et al. 2003), pathological conditions (van Emmerik et al. 1993; Corriveau et al. 2000b; Hagiwara et al. 2004), medication (Hasan et al. 1992; Agostini et al. 2004), low back pain (Nies and Sinnott 1991; Mientjes and Frank 1999; Radebold et al. 2001), exposure to vibration (Derave et al. 1998; Vuillerme et al. 2002), and dehydration (Derave et al. 1998).

A growing number of studies have reported an increase in postural sway with neuromuscular fatigue (Lundin et al. 1993; Johnston et al. 1998; Yaggie and McGregor 2002; Nussbaum 2003; Gosselin et al. 2004). Fatigue is an important factor to consider given that it is so closely associated with manual labor. Falls from heights are the leading cause of fatality in the construction industry (Derr et al. 2001), and loss of balance has been identified as influential in these falls (Hsiao and Simeonov 2001).

We previously reported an increase in COP-based measures of postural sway following lumbar extensor fatigue (Davidson et al. 2004). In an effort to expand upon these findings and further our understanding of the changes in the postural control system with fatigue, the first objective of this study was to investigate fatigue-related changes in 1) postural sway in separate anatomical planes (anteroposterior and mediolateral directions), 2) measures of postural steadiness (Corriveau et al. 2000a; Corriveau et al. 2004a), and 3) postural control via ankle stiffness (Winter et al. 2001).

Although many studies indicate that localized muscle fatigue causes increases postural sway, the possibility of a dose-response relationship between fatigue and sway has not been investigated. In other words, will increased levels of muscle fatigue lead to greater changes in postural sway? Muscle force producing capability, for example, has shown greater losses with increasing levels of fatigue (Viitasalo and Komi 1981; Hawkins and Hull 1993) and lactic acid accumulation (Fitts and Holloszy 1976). The second objective of this study was to investigate the effects of three different lumbar extensor fatigue levels (low, moderate, high) on postural sway.

The final objective of this investigation relates to the time over which fatigue is induced (fatiguing time). In settings outside the laboratory, fatigue is frequently induced over a matter of hours whereas previous studies investigating the effect of fatigue on sway induced fatigue over much shorter durations – minutes (Sparto et al. 1997; Yaggie and McGregor 2002). It is unclear if this difference in fatiguing time influences the measured effects of fatigue on sway. Therefore, the final objective of this investigation was to investigate the effects of fatiguing time on postural sway.

Methods

Twelve physically active males (20-22 years of age) participated in the experiment. Mean participant height and mass was 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.

Each participant attended four experimental sessions with at least one week between consecutive sessions. During each session, measures related to postural sway and control were collected both before and after a lumbar extensor fatiguing protocol to investigate changes with fatigue. In three of the experimental sessions, each participant was fatigued to one of three fatigue levels over 14 minutes. The fatigue levels were defined as low (86% of the unfatigued isometric maximum voluntary contraction (MVC) of the lumbar extensors), medium (73% MVC), and high (60% MVC). In the fourth session, the medium level of fatigue was repeated, but over a fatiguing time of 90 minutes. The four fatiguing conditions were presented to the twelve participants using a balanced Latin square replicated three times to balance presentation order.

The fatiguing protocol has been described in detail elsewhere (Davidson et al. 2004) and will only be summarized here. After a warm-up routine, maximum isometric lumbar extensor exertions were performed while the participant was positioned on a 45° Roman chair (New York Barbell, Elmira, NY), and force was recorded using a uniaxial load cell (Cooper Instruments and Systems, Warrenton, VA). Three unfatigued exertions were performed with one minute rest between each. Using the load cell data and an estimation of head, arms, and trunk mass and COM position (Zatsiorsky and King 1998) to correct for gravitational force on the upper body (Davidson et al. 2004), the corresponding lumbar extensor torque was estimated for all MVCs (at what level was the torque determined? E.g. L5/S1?). The largest of the three unfatigued torques was recorded as the unfatigued MVC.

Each participant performed multiple sets (one set per minute) of back extensions for the duration of the fatiguing exercise. Level of fatigue was assessed throughout the procedure by periodically measuring the participant's available strength during an MVC and plotting the values over time. The number of repetitions in each set was systematically changed so that MVC values decreased in a roughly linear manner. Two modifications to the previously reported fatiguing protocol were used here. First, immediate conversion of isometric force exertions to lumbar torque allowed more accurate assessment of fatigue. Second, these exertions were performed exactly ten seconds after completing the previous sent of back extensions. This latter modification standardized the time between the end of a set of back extensions and the MVCs.

Both before and after the fatiguing protocol, participants were instructed to "stand as still and as quietly as possible" for 30 seconds with their feet together, eyes closed, and arms at their sides. Three unfatigued standing trials were performed before the fatiguing protocol, and one fatiguing trial began approximately ten seconds following completion of the 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, and sampled at 1000 Hz, then passed through a 10 Hz low-pass software filter (zero-phase-lag 4^{th} order Butterworth) and transformed into COP data (Winter 1990). COM position in the mediolateral (ML) and anteroposterior (AP) directions were calculated from the COP data through double integration of COM acceleration and applying boundary conditions as described by Zatsiorsky and King (1998). COM trajectories were subsequently passed through a 3 Hz (Gage et al. 2004) low-pass filter (zero-phase-lag 4^{th} order Butterworth). Whole body segmental positions were also collected using a Vicon 460 motion analysis system (Vicon Motion Systems Inc., Lake Forest, CA) and then low-pass filtered (zero-phase-lag 4^{th} order Butterworth) with a 7 Hz cutoff frequency. Markers were placed over the acromion, iliac crest, greater trochanter, lateral femoral epicondyle, lateral malleolus, calcaneus, and head of the 5^{th} metatarsal. These data were collected mainly for another experiment, This data was used to calculate the COM height.

Several measures of postural sway were calculated from the COM signal (Priplata et al. 2002; Priplata et al. 2003) including four non-directional measures (mean velocity, sway area, mean radius, and maximum radius) and three directional measures in the AP and ML directions (mean velocity, range, and median frequency). Root mean square (RMS) of the COP-COM variable was calculated to assess changes in postural stability in the AP and ML directions

(Corriveau et al. 2000a; Corriveau et al. 2000b; Corriveau et al. 2001; Corriveau et al. 2004a; Corriveau et al. 2004b). To investigate potential changes in postural control, ankle stiffness values in the AP and ML directions were calculated using an inverted pendulum model (Carpenter et al. 2001; Winter et al. 2001; Winter et al. 2003). Differences between the fatigued trial and the mean of the three unfatigued trials were calculated for all dependent measures prior to statistical analyses.

The effect of fatigue on the postural sway and control measures was tested using a one-sample *t*-test with a test value of zero with data pooled across fatigue levels. The effects of fatigue level and fatigue time on postural sway and control were tested using a one-way repeated measures ANOVA. The independent variable in this analysis was fatiguing condition (four levels: 86 %MVC, 73 %MVC, 60 %MVC, and 73 %MVC/longer time). A significance level of 0.05 was used for all statistical tests. All statistical analyses were performed using SPSS (SPSS Inc., Chicago, IL).

Results

The modified lumbar extensor fatiguing protocol was demonstrated to be an effective means to fatigue participants below the desired %MVC level. After the fatiguing protocol, mean fatigue levels were 81.9 ± 4.5, 69.7 ± 4.5, and 59.9 ± 3.4 %MVC for the 14 minute protocols (were they significantly different from the target levels?. These values were significantly different from each other ($p<0.001$ for one-way ANOVA and post hoc Tukey HSD tests). The average fatigue level after the 90 minute protocol was 66.3 ± 3.4 %MVC, and was not significantly different from results in the shorter protocol ($p=0.182$ for paired *t*-test).

Fatigue affected several measures of postural sway and control. In regards to the non-directional sway measures, mean velocity increased ($p<0.001$) while mean radius and maximum radius decreased ($p<0.001$; $p=0.002$), respectively, following fatigue. Sway area was not affected by fatigue ($p=0.734$). Directional sway measures indicated differing effects of fatigue in the AP and ML directions (Figure 1). COM mean velocity in the AP direction increased ($p<0.001$) and median frequency increased ($p=0.028$). Range of AP amplitude did not show significant change ($p=0.348$). The ML direction showed changes in all measures: mean velocity (increase, $p=0.018$), median frequency (increase, $p<0.001$), and range (decrease, $p<0.001$). RMS of the COP-COM signal increased in the AP direction ($p<0.001$) and decreased in the ML direction ($p=0.010$). Analysis of ankle stiffness showed an increases in the AP ($p=0.025$) and ML ($p<0.001$) directions. The effect of fatigue condition was not significant for any dependent measures, indicating no significant effect of fatigue level or fatigue time on measures of postural sway and control. These results are summarized in Table 1.

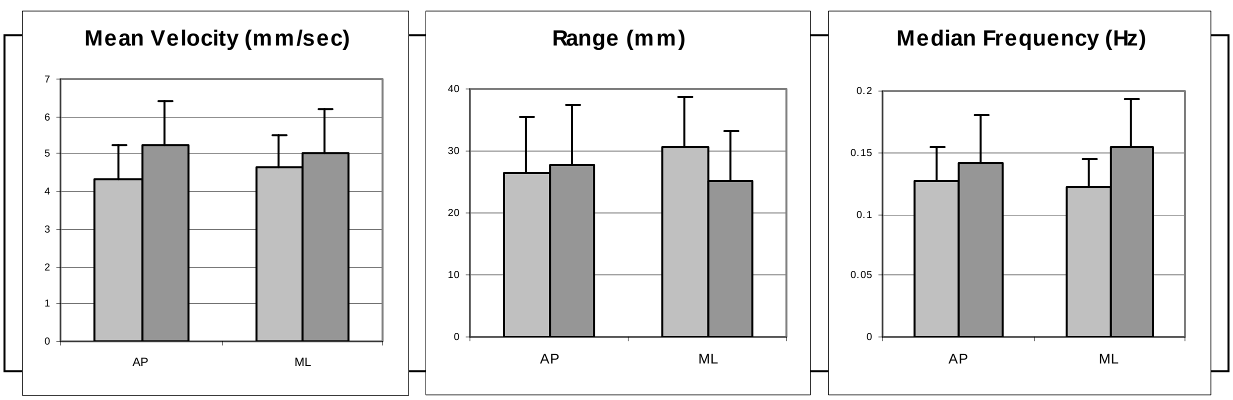

Figure 1: Unfatigued (light bars) and fatigued (dark bars) directional measures of postural sway averaged across all participants. Error bars indicate standard deviation. Similar results were found for AP and ML directions in mean velocity and median frequency measures. Range of excursion, however, showed differences between the two directions. All changes were statistically significant except for range of excursion in the AP direction.

Table 1: Summary of mean (standard deviation) postural measures before and after lumbar extensor fatigue.

	% change	Unfatigued	Fatigued
Non-directional COM Measures			
mean velocity ($mm \cdot sec^{-1}$)	14.0 ↑ *	7.07 (1.28)	8.07 (1.63)
sway area ($mm^2 \cdot sec^{-1}$)	2.1 ↓	0.21 (0.09)	0.21 (0.10)
mean radius (mm)	14.9 ↓ *	9.07 (2.62)	7.72 (2.62)
max radius (mm)	12.2 ↓ *	21.0 (5.5)	18.5 (5.4)
AP Postural Measures			
mean velocity ($mm \cdot sec^{-1}$)	19.8 ↑ *	4.35 (0.90)	5.21 (1.18)
range (mm)	4.1 ↑	26.6 (8.8)	27.7 (9.9)
median frequency (Hz)	10.8 ↑ *	0.13 (0.03)	0.14 (0.04)
RMS of COP-COM (mm)	2.9 ↑ *	0.46 (0.03)	0.47 (0.03)
Stiffness ($N \cdot mm \cdot rad^{-1}$)	1.8 ↑ *	618.3 (78.1)	629.6 (80.7)
ML Postural Measures			
mean velocity ($mm \cdot sec^{-1}$)	8.3 ↑ *	4.64 (0.86)	5.02 (1.16)
range (mm)	18.2 ↓ *	30.7 (8.1)	25.1(8.1)
median frequency (Hz)	27.1 ↑ *	0.12 (0.02)	0.16 (0.04)
RMS of COP-COM (mm)	0.6 ↓ *	0.46 (0.03)	0.45 (0.02)
Stiffness ($N \cdot mm \cdot rad^{-1}$)	10.4 ↑ *	509.3 (74.4)	562.2 (84.4)

* indicates a significant change following fatigue ($p<0.05$)

Discussion

The first objective of this study was to further our understanding of the changes in postural sway and control with lumbar extensor fatigue by employing additional measures of postural sway, postural steadiness, and ankle stiffness. Non-directional measures of postural sway indicated an overall increase in sway velocity and a decrease in sway amplitude with fatigue. In the AP direction, fatigue increased sway velocity and frequency, and did not change sway range. In the ML direction, fatigue similarly increased sway velocity and frequency, but also decreased sway range. COP-COM values suggested a loss of steadiness in the AP direction, and increased steadiness in the ML direction. Stiffness, as estimated by an inverted pendulum model, increased in both AP and ML directions. Overall, these results indicate a differential effect of fatigue between the AP and ML directions, and suggest a change in postural control strategy with fatigue.

Growing evidence supports the role of both feedforward and feedback mechanisms in postural control (Figure 2). Winter et al. (1998; 2001), for example, have demonstrated the effectiveness of active ankle stiffness as a simple feedforward mechanism for maintaining a standing posture. At the same time, it is well accepted that the CNS integrates feedback information from the visual, vestibular, and somatosensory systems for reactive balance control (Mirka and Black 1990; Shumway-Cook and Woollacott 1995). The increase in stiffness following lumbar extensor fatigue (shown in Figure 3) suggests an increased reliance on feedforward control of posture. A potential reason for this shift toward feedforward control of posture may be a degradation of feedback information with fatigue. A number of investigations have linked localized muscular fatigue with decreases in proprioceptive acuity , and in particular, this phenomenon has been documented at the lumbar spine (Taimela et al. 1999). Although lumbar extensor proprioceptive acuity was not measured in this study, a post hoc analysis indicated a 59% and 33% increase in movement at the lumbar spine during quiet standing in both the AP and ML directions, respectively ($p<0.001$). Increased movement at the lumbar spine would be expected with a loss of proprioceptive acuity. Also supporting loss of proprioceptive acuity as a reason for shifting postural control strategy, some evidence indicates that the CNS may reduce its dependency on proprioceptive afferents from regions of the body altered by fatigue (Pedersen et al. 1998; Vuillerme et al. 2002).

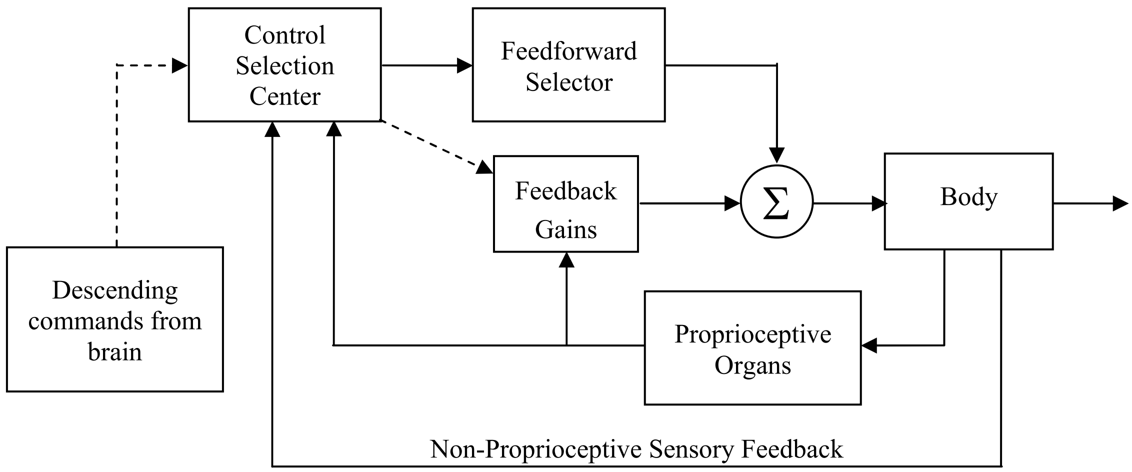

Figure 2: Control flow diagram similar to that found in Kuo (1995). The CNS Control Selection Center receives afferent sensory signals from the body. Upon processing this information, two feedforward strategies of balance control, which are not exclusive, are employed during quiet stance. A change in feedforward stiffness and/or a reweighing of sensory information is engaged in feedback control.

In light of this evidence that the CNS shifts toward more feedforward control with lumbar extensor fatigue, it is unclear how this is accomplished. Perhaps a form of strategy selection is incorporated to compensate for changes such as fatigue, using both proprioceptive and non-proprioceptive signals from the body. In particular, physiological changes associated with muscle fatigue, such as localized pain (via nociceptor activity) or decreased pH due to elevated lactic acid levels, may serve as triggering mechanisms for strategy changes.

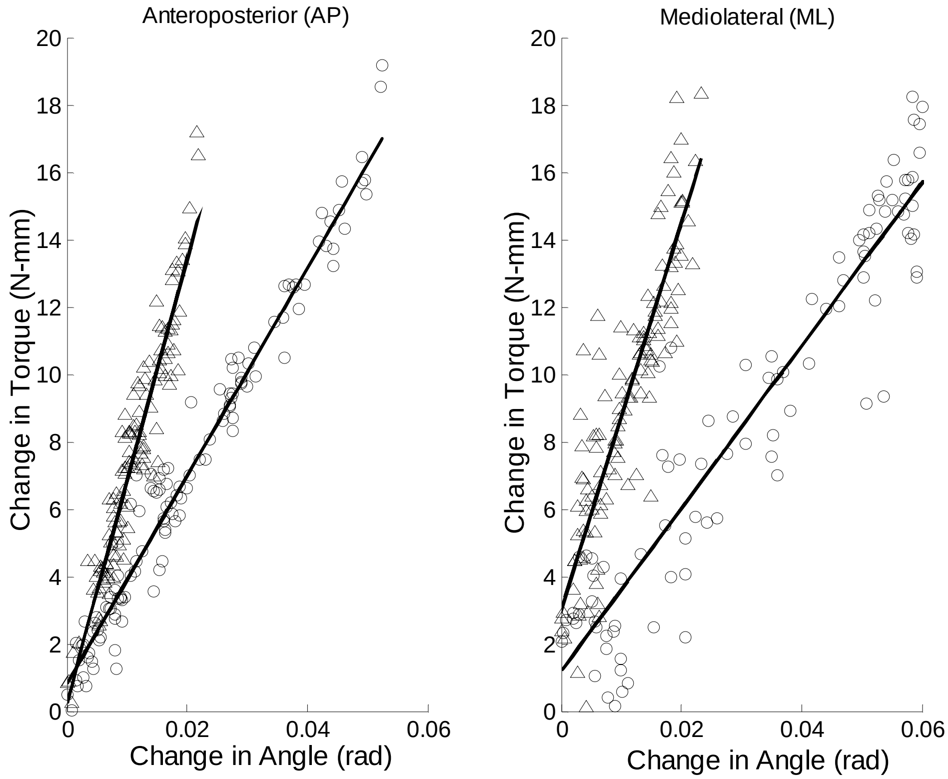

Figure 3: Sample data used to calculate unfatigued and fatigued feedforward stiffness values (○ – unfatigued values, △ – fatigued values). As can be seen, the data generally had a linear trend which accommodated a linear least-squares fit. Both AP and ML directions demonstrated significant increases in stiffness following lumbar extensor fatigue.

The COP-COM signal has been described as the "error" signal in balance control between the controlling variable (COP) and the controlled variable (COM) (Winter 1993). Thus, an increase in the COP-COM signal indicates a loss of postural steadiness and/or greater difficulty in postural control, and a decrease in COP-COM indicates improved postural steadiness and/or less difficulty in postural control. Our results showed a slight decrease in COP-COM in the ML direction (Figure 4), suggesting the purported change in strategy from feedback to more of feedforward control (as evidenced by a 10.4% increase in stiffness) was effective at helping to control sway. We also found an increase in COP-COM in the AP direction (Figure 4), suggesting the change in strategy (only a 1.8% increase in the AP direction) did not completely offset losses in control associated with fatigue.

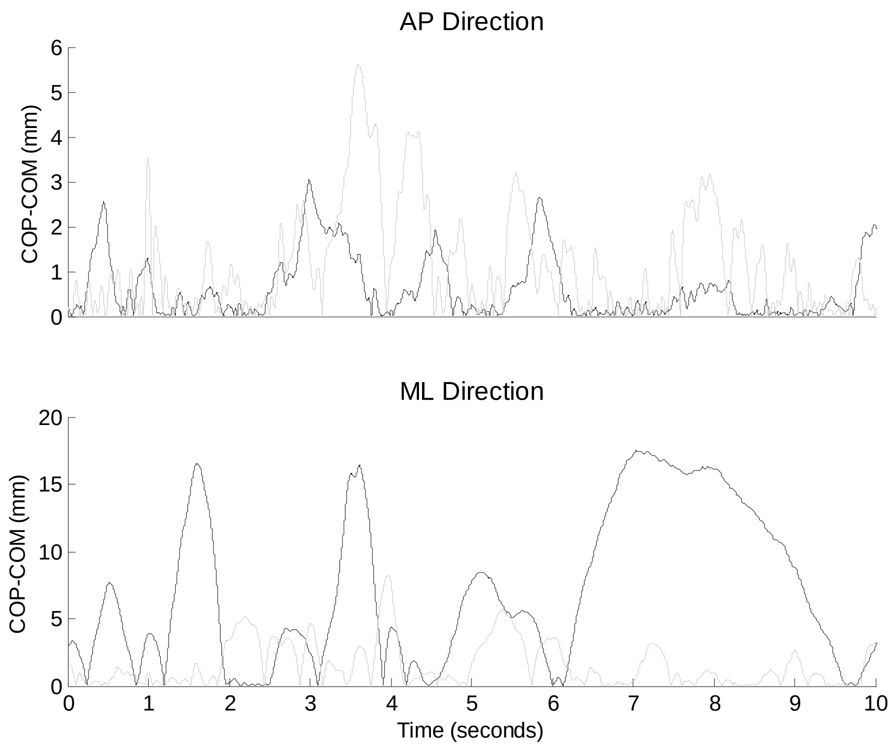

Figure 4: Absolute value of unfatigued and fatigued COP-COM signal in AP and ML directions for first ten seconds of a participant. Unfatigued and fatigued values are overlaid for comparison. Notice the increase in fatigued COP-COM amplitude in the AP direction with a simultaneous decrease in fatigued COP-COM amplitude in the ML direction.

We also aimed to determine the effects of fatigue level and fatiguing time on postural sway. Our results revealed no differences in fatigue effects among the different fatigue levels. Contrary to our hypothesis, a dose-response relationship of fatigue level with sway was not found. A post hoc power analysis was not pursued because visual inspection of the data revealed no trends suggesting a fatigue level effect. Our results also revealed no differences in fatigue effects among the two fatiguing times investigated. Despite improvements in our fatiguing protocol, these results are consistent with our earlier findings (Davidson et al. 2004).

The present study shows some seemingly differing effects of lumbar extensor fatigue on sway measures results compared to our earlier study investigating the effects of lumbar extensor fatigue on COP-based measures of postural sway (Davidson et al. 2004). Both studies found an increase in sway mean velocity, but the earlier study also found increases in area measures which area not found here. The earlier study also found no change in sway frequency, whereas increases were reported here. These conflicting results may be partly attributed to the fact that the earlier study used COP-based measures of postural sway whereas the current study used COM-based measures of sway. In fact, previous studies of fatigue effects on postural control have shown differences in COP and COM measurements (Caron 2003; Caron 2004).

Two potential limitations to this investigation warrant discussion. First, these conclusions reflect the results found in a group of young, healthy, and physically active males. Results may differ in other subject populations. Second, variability may have been introduced by participant motivation level during lumbar extensor MVCs and sway measurements. However, MVC measures have been shown to be valid measures of fatigue (Bigland-Ritchie et al. 1995) and fall risk (Lichtenstein et al. 1989; Riach and Starkes 1994). The last sentence contains claims that are a bit too bold, especially since both can be criticized.

Conclusions

Lumbar extensor fatigue had differential effects on sway and sway control in AP and ML directions, and observed increases in ankle stiffness suggest a shift toward greater reliance on feedforward control of balance compared to feedback control. Fatiguing participants to different levels of fatigue and over different fatiguing times did not affect the magnitude of changes in postural sway and control associated with fatigue.

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APPENDIX

FATIGUE TIME STUDY

<u>Setup Checklist</u>

☐ 1. Turn on: (allow 30 minutes to warm up)
- force platform amplifier
- load cell amplifier
- EMG amplifier

☐ 2. Create computer directory with subject initials and date (i.e. *mm021002_*)

☐ 3. Get out supplies
- EMG electrodes
- reference electrode
- Co-flex
- alcohol
- athletic tape
- razor
- bathroom scales

FATIGUE TIME STUDY (short protocol)
Data Collection Sheet

Subject name:________________________ Date:______________ Start time:______

☐ 1. Make sure subject is wearing proper clothing (t-shirt, shorts, socks)
☐ 2. Give summary of protocol and demonstrate
☐ 3. Obtain informed consent
☐ 4. Ask subject if they need to use the restroom
☐ 5. Turn on music
☐ 6. Ask subject to remove shoes
☐ 7. Collect anthropometric measurements:
  age: _______
  weight: _______ lbs
  height: _______ cm
☐ 8. Adjust height of roman chair
☐ 9. Ask subject to replace shoes
☐ 10. Apply EMG electrodes
  reference electrode
  erectus abdominus - 2 cm lateral, 3 cm superior to naval
  external oblique - 10 cm lateral to naval
  erector spinae - 4 cm lateral to L3 (find iliac spine)
  internal oblique
  note: be sure to secure wires and check for EMG signal
☐ 11. Warm-up exercise (2 sets)
  2 ½ minutes jogging at 4.5 mph
  back stretching
  3 back extensions
☐ 12. Ask subject to remove shoes
☐ 13. Put on webbing correctly
☐ 14. Connect subject to EMG amplifier
☐ 15. Perform MVCs:
  file # ___ erector spinae load cell max: ________volts ________volts
  ___ internal oblique
  ___ erectus abdominus
  ___ external oblique
☐ 16. Enter MVC voltage into Excel spreadsheet
  weight to be used for box lift (20% MVC) _______ lbs
☐ 17. 1 minute rest (place appropriate weight in box)
☐ 18. Zero the forceplate amplifier
☐ 19. Measure unfatigued balance time: **30 sec** file # ____ comments: ____________________
☐ 20. Measure unfatigued box lift time: **5 sec** file # ____ comments: ____________________
☐ 21. Disconnect electrodes from EMG preamplifier
☐ 22. Start metronome (30 reps per minute)
☐ 23. Start fatigue protocol

Time	Target Voltage	Actual Voltage	Reps per minute	Comments
0				
6				
12				
18				
24				
30				
36				
42				
48				
54				
60				
66				
72				
78				
84				
90				

90-minute linear fatigue protocol:
- Extensions will be done through full 45° range of motion at a rate of 30 reps/min
- Begin with initial rate of 3 repetitions every minute (rem)
- Final MVC defined as two consecutive MVC falling below desired %
- MVC will be measured at 6 minute increments using a load cell throughout fatigue and compared to linear regression of target voltage.

    If measured voltage is within ± 5% initial MVC of target, increase rem by 1
    If measured voltage > target voltage plus 5% initial MVC voltage, increase rem by 2
    If measured voltage < target voltage minus 5% initial MVC voltage, rem remains the same
    If measured voltage < target voltage minus 15% initial MVC voltage, decrease rem by 1

Remind subject to keep feet flat and move through full range of motion.

☐ 24. Attach electrodes to EMG preamplifier

☐ 25. Measure fatigued balance time: **30 sec** file # ____ comments: ______________________

☐ 26. Measure fatigued box lift time: **5 sec** file # ____ comments: ______________________

☐ 27. Repeat steps 25-26 every 5 minutes for 30 minutes
- subject should remain standing

5 min:
Measure fatigued balance time: **30 sec** file # ____ comments: ______________________
Measure fatigued box lift time: **5 sec** file # ____ comments: ______________________

10 min:
Measure fatigued balance time: **30 sec** file # ____ comments: ______________________
Measure fatigued box lift time: **5 sec** file # ____ comments: ______________________

15 min:
Measure fatigued balance time: **30 sec** file # ____ comments: ______________________
Measure fatigued box lift time: **5 sec** file # ____ comments: ______________________

20 min:
Measure fatigued balance time: **30 sec** file # ____ comments: ______________________
Measure fatigued box lift time: **5 sec** file # ____ comments: ______________________

25 min:
Measure fatigued balance time: **30 sec** file # ____ comments: ______________________
Measure fatigued box lift time: **5 sec** file # ____ comments: ______________________

30 min:
Measure fatigued balance time: **30 sec** file # ____ comments: ______________________
Measure fatigued box lift time: **5 sec** file # ____ comments: ______________________

☐ 28. Offer subject a chair to rest

☐ 29. Record end time :______

☐ 30. Remove EMG and harness from subject.
Give them stipend.
Thank them, and see them out the door.

☐ 31. Turn off system:
- force platform amplifier
- load cell amplifier
- EMG amplifier

☐ 32. Clean up the laboratory

FATIGUE LEVEL STUDY

Setup Checklist

 1. Turn on: (allow 30 minutes to warm up)
    - Vicon datastation
    - force platform amplifier
    - load cell amplifiers
    - EMG amplifier
    - DAQPad-6020E
 2. Open Excel Spreadsheet (*MVC Regression.xls*) for fatigue protocol and save as *subjectname.xls* in subject folder.
 3. Open *load cell–emg.vi* for EMG collection and real-time load cell viewing
 4. Open workstation software and create Vicon directory with subject name and session number
 5. Get out supplies:
    - EMG electrodes
    - Co-flex
    - alcohol
    - athletic tape
    - razor
    - bathroom scale
    - reflective markers (17)
 6. Calibrate Vicon Cameras
    Make sure calibration is adequate:
    System > Calibrate cameras
    wand visibility > 70 %
    static reproducibility < 1.0%
 7. Check Vicon data collection setting
    System > Video Setup
    video sampling rate: 100Hz
    System > Analog Setup
    analog sampling rate: 1000 Hz
    collection channels 1-7 (apply to current session)
 8. Make sure that forceplate is not in contact with platform

FATIGUE LEVEL STUDY

Data Collection Sheet

Subject name: _________________________________ Date: _______________
Session # _____ Fatigue Level: _________ Start time: _________

- ☐ 1. Give subject proper clothing in which to change (shorts, tank top) and ask if they need to use the restroom
- ☐ 2. Give summary of protocol and demonstrate
- ☐ 3. Obtain informed consent
- ☐ 4. Ask subject to remove shoes
- ☐ 5. Collect anthropometric measurements:
  age: _______ weight: _______ lbs height: _______ cm
- ☐ 6. Position subject on forceplate leaving a 10 cm gap from back to resting pendulum. Mark toe line and edges of base of support with tape and record dimensions position of front left corner of base of support for Time-to-Boundary calculations:
  width: _______ cm length: ________ cm
  _______ cm from posterior edge ________ cm from left edge
- ☐ 7. Adjust pendulum height Record height: _______
- ☐ 8. Adjust height of roman chair Record height: _______
- ☐ 9. Demonstrate balance measurement with pendulum
- ☐ 10. Ask subject to replace shoes
- ☐ 11. Place harness loosely onto subject
- 12. Apply EMG electrodes:
  - ☐ reference electrode (head of fibula)
  - ☐ erectus abdominus (2 cm lateral, 3 cm superior to naval)
  - ☐ external oblique (10 cm lateral to naval)
  - ☐ erector spinae (4 cm lateral to L3 – even with iliac crest)
  - ☐ internal oblique
- ☐ 13. Apply reflective markers:
  - ☐ right shoulder ☐ right iliac crest ☐ right back
  - ☐ right elbow (radial) ☐ right greater trochanter
  - ☐ right wrist (ulnar) ☐ right lateral epicondile
  - ☐ left shoulder ☐ left iliac crest
  - ☐ left elbow (radial) ☐ left greater trochanter
  - ☐ left wrist (ulnar) ☐ left lateral epicondile
- ☐ 14. Warm-up exercise (2 sets)
  - 2 ½ minutes jogging at 4.5 mph
  - back stretching
  - 5 back extensions
- ☐ 15. Ask subject to remove shoes and socks
- 16. Apply remaining reflective markers
  - ☐ right temple ☐ right maleolus
  - ☐ left temple ☐ left maleolus
  - ☐ forehead ☐ right 5th metatarsal
  - ☐ back of head ☐ left 5th metatarsal
- ☐ 17. Connect subject to EMG preamplifier
- ☐ 18. Check for EMG signal using LabView
- ☐ 19. Tighten harness

20. Perform MVCs: (LabView collection)

- □ erector spinae
  load cell max: ________ volts ________ volts ________ volts
  filename: *EMG* ___ gain setting: ___
- □ internal oblique filename: *EMG* ___ gain setting: ___
- □ erectus abdominus filename: *EMG* ___ gain setting: ___
- □ external oblique filename: *EMG* ___ gain setting: ___

□ 21. Apply heel markers

□ 22. Enter erector spinae MVC voltage into Excel spreadsheet
record weight to be used for box lift (20% of MVC load cell force): _______ lbs

□ 23. Put weight into box

□ 24. Zero forceplate amplifier

□ 25. Collect static marker calibration
(trial type: *subject calibration*)
filename: *collection* __ comments: ________________________

□ 26. Label subject markers in Vicon (*trial* > *create autolabel calibration* , *save trial*)

□ 27. Collect unfatigued balance ***(dynamic)***
(trial type: *repeated capture*)
filename: *collection* __ comments: _________________________
filename: *EMG* __ comments: _________________________

One minute rest
Collect unfatigued balance ***(dynamic)***
filename: *collection* __ comments: _________________________
filename: *EMG* __ comments: _________________________

One minute rest
Collect unfatigued balance ***(dynamic)***
filename: *collection* __ comments: _________________________
filename: *EMG* __ comments: _________________________

One minute rest
Collect unfatigued box lift time: **5 sec**
filename: *EMG* __ comments: _________________________

□ 28. Start metronome (30 beats per minute)

□ 29. Begin fatiguing protocol

<u>Fatiguing Protcol</u> **Fatigue level: _______**

Time	% MVC	Reps per minute	Comments
0 : 00	100		
5 :			
11 :			
17 :			
23 :			
29 :			
35 :			
41 :			
47 :			
53 :			
59 :			
65 :			
71 :			
77 :			
83 :			
89 :			
91 :			
93 :			

Linear fatigue protocol:

- Extensions will be done through full 45° range of motion at a rate of approximately30 reps/min

- Begin with number of repetitions every minute (rem) specified below

- Final MVC defined as two consecutive MVC falling below desired %

- MVC will be measured throughout protocol at exactly 10 seconds after completing every other set using load cell and compared to linear regression of target MVC calculated in Excel Speadsheet *MVC regression.xls*

Goal MVC	*Beginning # of Reps*
86.6 %	*5*
73.3 %	*9*
60 %	*11*

Change in repetitions			
Above $^{+}$5 %	***Within ±5 %***	***Below $^{-}$5 %***	***Below $^{-}$15 %***
+ 2	**+ 1**	**+ 0**	**- 1**

☐ 30. Collect fatigued balance ***(dynamic)***
filename: *collection* __ comments: ___________________________
filename: *EMG* __ comments: ___________________________

☐ 31. Measure fatigued box lift time: **5 sec**
filename: *EMG* __ comments: ___________________________

☐ 32. Collect balance and lifting data every 3 minutes for 30 minutes
note: subject should remain standing at all times

3 min:
Collect fatigued balance ***(static only)***
filename: *collection* __ comments: ___________________________

6 min:
Collect fatigued balance ***(dynamic)***
filename: *collection* __ comments: ___________________________
filename: *EMG* __ comments: ___________________________
Collect fatigued box lift time: **5 sec**
filename: *EMG* __ comments: ___________________________

9 min:
Collect fatigued balance ***(static only)***
filename: *collection* __ comments: ___________________________

12 min:
Collect fatigued balance ***(dynamic)***
filename: *collection* __ comments: ___________________________
filename: *EMG* __ comments: ___________________________
Collect fatigued box lift time: **5 sec**
filename: *EMG* __ comments: ___________________________

15 min:
Collect fatigued balance ***(static only)***
filename: *collection* __ comments: ___________________________

18 min:
Collect fatigued balance ***(dynamic)***
filename: *collection* __ comments: ___________________________
filename: *EMG* __ comments: ___________________________
Collect fatigued box lift time: **5 sec**
filename: *EMG* __ comments: ___________________________

21 min:
Collect fatigued balance ***(static only)***
filename: *collection* __ comments: ___________________________

24 min:
Collect fatigued balance ***(dynamic)***
filename: *collection* __ comments: ___________________________
filename: *EMG* __ comments: ___________________________
Collect fatigued box lift time: **5 sec**
filename: *EMG* __ comments: ___________________________

27 min:
Collect fatigued balance ***(static only)***
filename: *collection* __ comments: ___________________________

30 min:

Collect fatigued balance *(dynamic)*

filename: *collection* __ comments: _______________________

filename: *EMG* __ comments: _______________________

Collect fatigued box lift time: **5 sec**

filename: *EMG* __ comments: _______________________

□ 33. Offer subject a chair to rest

□ 34. Record end time: _______

□ 35. Remove EMG, harness, and reflective markers from subject.
Give them stipend and have them sign payment sheet.
Thank them, and see them to the door.

□ 36. Mark Vicon files for batch process and export to ASCII format through 'pipeline'

□ 37. Transfer Vicon files to network drive

□ 38. Turn off equipment:
- Vicon system
- force platform amplifier
- load cell amplifier
- EMG amplifier
- DAQPad-6020E

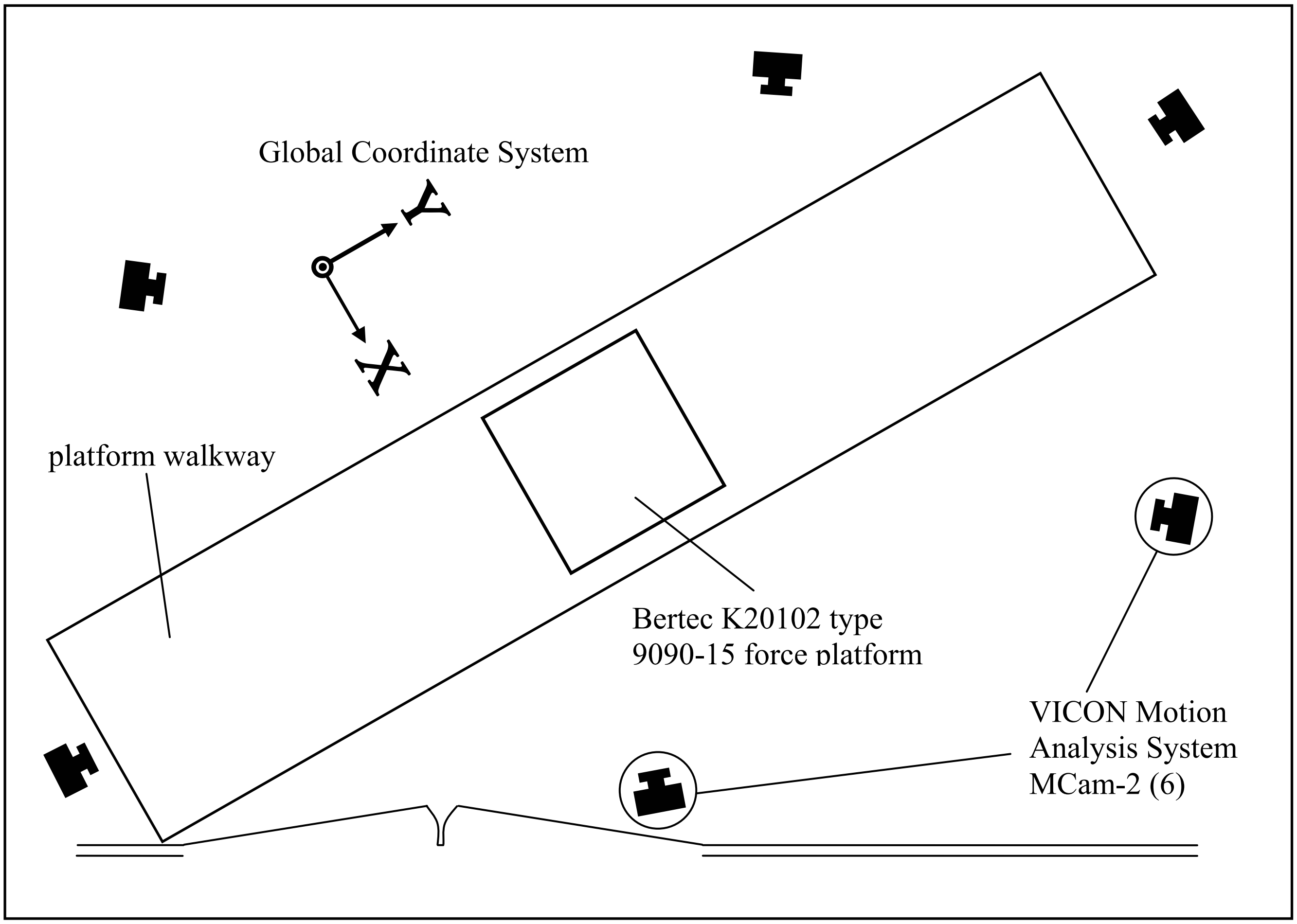
□ 39. Reapply adhesive to reflective markers

□ 40. Clean up the laboratory

General Comments:

____
____
____
____
____
____
____
____
____

Laboratory Setup



Center of pressure data was collected by Bertec K20102 type 9090-15 force platform and marker position data was collected with the VICON 460 Motion Monitoring System as seen in the configuration above.

Virginia Tech
VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

Institutional Review Board

Dr. David M. Moore
IRB (Human Subjects) Chair
Assistant Vice Provost for Research Compliance
CVM Phase II - Duckpond Dr., Blacksburg, VA 24061-0442
Office: 540/231-4991; FAX: 540/231-6033
e-mail: moored@vt.edu

13 December 2002

MEMORANDUM

TO: Michael Madigan ESM 0219

FROM: David M. Moore

SUBJECT: **Expedited Approval – "Effects of Low Back Fatigue on Balance"** – IRB # 02-581

Jeffress grant

This memo is regarding the above-mentioned protocol. The proposed research is eligible for expedited review according to the specifications authorized by 45 CFR 46.110 and 21 CFR 56.110. As Chair of the Virginia Tech Institutional Review Board, I have granted approval to the study for a period of 12 months, effective December 13, 2002.

Approval of your research by the IRB provides the appropriate review as required by federal and state laws regarding human subject research. It is your responsibility to report to the IRB any adverse reactions that can be attributed to this study.

To continue the project past the 12 month approval period, a continuing review application must be submitted (30) days prior to the anniversary of the original approval date and a summary of the project to date must be provided. My office will send you a reminder of this (60) days prior to the anniversary date.

cc:File
OSP 0170

Virginia Tech
VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

Institutional Review Board

Dr. David M. Moore
IRB (Human Subjects) Chair
Assistant Vice Provost for Research Compliance
CVM Phase II - Duckpond Dr., Blacksburg, VA 24061-0442
Office: 540/231-4991; FAX: 540/231-6033
e-mail: moored@vt.edu

February 5, 2003

MEMORANDUM

TO: Michael Madigan ESM 0219

FROM: David M. Moore

SUBJECT: **Expedited Approval** – "Effects of fatigue time on balance degeneration and recovery" – IRB # 03-052

Pilot study for Jeffress gro
(Effects of fatigue time on balance degeneration

This memo is regarding the above-mentioned protocol. The proposed research is eligible for expedited review according to the specifications authorized by 45 CFR 46.110 and 21 CFR 56.110. As Chair of the Virginia Tech Institutional Review Board, I have granted approval to the study for a period of 12 months, effective February 3, 2003.

Approval of your research by the IRB provides the appropriate review as required by federal and state laws regarding human subject research. It is your responsibility to report to the IRB any adverse reactions that can be attributed to this study.

To continue the project past the 12 month approval period, a continuing review application must be submitted (30) days prior to the anniversary of the original approval date and a summary of the project to date must be provided. My office will send you a reminder of this (60) days prior to the anniversary date.

cc:File

Vita

Bradley Steven Davidson

Bradley Davidson was born in Knoxville, Tennessee on September 15, 1979. He attended Cocke County High School in Newport, Tennessee and was honored as Valedictorian. He completed a Bachelor of Science in Civil Engineering, graduating Summa Cum Laude from Tennessee Technological University in 2002. He obtained a Master of Science Degree in Engineering Mechanics with a Biomedical Engineering option from Virginia Polytechnic and State University. During this period, he received an award for Outstanding Researcher at the 3rd Virginia Tech – Wake Forest University School of Biomedical Engineering and Sciences Student Research Symposium. His research was conducted in the Virginia Tech Musculoskeletal Biomechanics Laboratory on the topic of localized neuromuscular fatigue effects on the postural control system, and has been published in peer reviewed biomechanical journals and conference proceedings. He will pursue a PhD in Biomedical Engineering in the Virginia Tech – Wake Forest School of Biomedical Engineering and Sciences, and aspires to one day obtain a position as teaching faculty in engineering. In his free time he enjoys spending time with his wife, Becky, and can often be found outside rock climbing, cycling, or backpacking.

Bradley Davidson can be contacted at the following address:

1745 Donlee Drive
Blacksburg, Virginia 24060