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Lumbar extensor fatigue and circumferential ankle pressure impair ankle joint motion sense

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Abstract

Fatigue of the lumbar extensor muscles has been associated with a degradation of balance, but the mechanism is not well understood. The ankle plays a major role in upright standing, and loss of proprioceptive acuity at the ankle could contribute to a degradation of balance. Therefore, the first objective of this study was to investigate the effect of lumbar extensor fatigue on ankle proprioceptive acuity. The second objective was to investigate the effect of circumferential ankle pressure (CAP) on ankle proprioceptive acuity to evaluate CAP as a potential intervention to mitigate any loss of proprioceptive acuity at the ankle with lumbar extensor fatigue. To address these objectives, ankle joint motion sense was evaluated with and without CAP, both before and after the lumbar extensors were fatigued. Results showed an impairment in joint motion sense with both fatigue and CAP. These results indicate that lumbar extensor fatigue impairs ankle proprioceptive acuity, which may help explain observed increases in postural sway subsequent to lumbar extensor fatigue.

Keywords: Proprioception; Kinesthesia; Falls

Falls from heights are responsible for injuring an estimated 100,000 construction workers in the United States each year [29]. To develop strategies to help prevent these falls, it is prudent to investigate factors that can contribute to a loss of balance. Localized muscle fatigue is one factor that has been shown to increase postural sway during quiet stance (which is commonly associated with a degradation of balance). For example, an increase in postural sway has been shown following fatigue in the ankle [3,20,38,39,41], fatigue from repetitive lifting [35], cardiovascular and lower extremity fatigue from running and cycling [13,23,27], and with localized shoulder fatigue from prolonged overhead work [28]. Similarly, a previous study from our laboratory found an increase in postural sway with lumbar extensor fatigue [6]. However, it is unclear at this point how lumbar extensor fatigue impairs balance.

Muscle fatigue has been associated with a loss of proprioceptive acuity in various muscles [2,4,22,34]. Taimela et al. [36] reported impairment in the ability to sense a change in lumbar position following lumbar fatigue. As such, a loss of proprioceptive acuity in the lumbar extensors with fatigue may result in larger movements at the lumbar spine during quiet standing, and a concomitant increase in postural sway. However, the inverted pendulum model of balance [11] suggests a minor role of the lumbar extensors for maintaining balance in the sagittal plane. Thus, changes in proprioceptive acuity in a muscle group with a “minor role” in balance, such as the lumbar extensors, may not contribute significantly to the increase in sway with fatigue. The ankle musculature, however, does play a dominant role in maintaining balance in the sagittal plane during quiet standing. A degradation of proprioceptive acuity at the ankle with lumbar extensor

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fatigue could account for the increase in sway with low back fatigue. While not intuitive, deleterious effects of fatigue on proprioceptive acuity at joints distal to the fatigue site have been reported [33]. Thus, the first objective of this study was to evaluate the effect of lumbar extensor fatigue on ankle proprioceptive acuity.

Circumferential ankle pressure (CAP) has been shown to improve ankle proprioceptive acuity in individuals with below average proprioceptive acuity [42]. Others have reported that circumferential wrist pressure improved accuracy in wrist position sense, particularly in elderly individuals with age-related deterioration in proprioceptive acuity [1]. In both of these studies, circumferential joint pressure may improve proprioceptive acuity by augmenting feedback from mechanoreceptors in the skin, making them more sensitive to skin movement associated with joint movement. Extending this idea to situations involving muscle fatigue, augmented mechanoreceptor feedback in the presence of muscle fatigue may offset the deleterious effect of fatigue on proprioceptive acuity. If lumbar extensor fatigue degrades proprioceptive acuity at the ankle, it is possible that CAP could mitigate any deleterious effects of fatigue on ankle proprioceptive acuity. Therefore, the second objective of this study was to investigate the effect of CAP on ankle proprioceptive acuity both with and without lumbar extensor fatigue.

Fourteen healthy male subjects participated in the experiment. Their age was 23.6 ± 2.9 years (mean ± standard deviation) with mass and height of 83.6 ± 12.4 kg and 184.8 ± 8.8 cm, respectively. All subjects reportedly exercised two to four times a week, and had experienced no ankle injuries within the last 12 months. This experiment was conducted in accordance with the Declaration of Helsinki, and all subjects provided informed consent in accordance with the Virginia Tech Institutional Review Board before participation.

Proprioceptive acuity in this study was quantified by ankle joint motion sense (JMS). JMS, also termed joint kinesthesia, is the angular displacement of a joint necessary to detect joint motion. JMS was measured in all subjects with and without CAP both before and after a lumbar fatiguing protocol. Before the fatigue protocol, three JMS measurements were performed in plantar flexion and dorsiflexion both with and without CAP. The presentation order of movement direction and CAP condition was counterbalanced so that half of the subjects would get one condition or one direction first and the other half would get the other condition or direction first. After the fatigue protocol, the same procedure was followed except that only one trial was completed in each direction and each CAP condition in order to minimize recovery from fatigue. All JMS measurements were completed within 5 min from the end of the fatigue protocol. Based on earlier work that postural sway took >20 min to recover after lumbar extensor fatigue [6], we felt that any effects of fatigue on ankle proprioceptive acuity would last longer than the 5 min required for JMS measurements.

JMS was measured using a Biodex System 3 Pro dynamometer (Shirley, New York). Subjects were seated supine on the Biodex chair with the thigh of the dominant leg (self-reported) resting on a support pad (Fig. 1). The subject's bare foot was attached to the footplate with a Velcro strap and the lateral malleolus was aligned with the axis of rotation of the dynamometer. In this position, the ankle being tested was in the anatomical position. Subjects were asked to lie back in the chair with their eyes closed to remove any visual cues,

Fig. 1. Subject seated in Biodex System 3 dynamometer for JMS testing.

and headphones playing music were worn to mask any audio cues produced by the dynamometer. A hand-held massager (Sensa-Touch, Dr. Scholl's, El Paso, TX, USA) was hung from the footplate to provide a small background vibration to the foot to conceal any vibration associated with operating the dynamometer motor. To measure JMS, the ankle was passively moved by the dynamometer at a velocity of 0.25°/s in either plantar flexion or dorsiflexion. Similar rates of rotation have been used by other investigators [24,25] and these tests were shown to have excellent repeatability [7]. After the massager was activated, the rotation of the footplate started following a random delay of 1–10 s to discourage guessing by the subjects. Subjects were asked to concentrate on the initiation of ankle movement and to press a stop button when footplate motion was detected, thereby stopping rotation of the footplate.

CAP was applied using a pediatric blood pressure cuff (Omron, True Gage Cuff, Bannockburn, IL, USA) placed just superior to the medial and lateral malleoli. This position was used in an earlier study of CAP [42] and allows free ankle motion while theoretically providing additional tactile stimulation. The cuff was inflated to a pressure of 60 mmHg and monitored throughout the test to ensure that the pressure was held constant.

The fatigue protocol has been described in detail elsewhere [6]. Briefly, after a warm-up, subjects were fitted to a construction harness and positioned on a 45° Roman Chair (New York Barbell, Elmira, NY, USA). Three initial maximum voluntary contractions (MVC) of the lumbar extensors were performed by having subjects pull against a load cell (Cooper, Warrenton, VA, USA) that anchored the construction harness to the Roman Chair. Subjects were asked to pull evenly and consistently for several seconds for each MVC and not to "jerk" the load cell at the onset of the MVC. Using the load cell data and an estimation of head, arms and trunk mass and COM position [43] to correct for gravitational force on the upper body, the corresponding torque at the 'lumbar joint' (L3) was estimated for all MVCs [6]. The largest of the three unfatigued torques was recorded as the unfatigued MVC. The protocol was designed to fatigue subjects to 75% of their MVC by performing a set of back extensions on the Roman Chair each minute for 14 min. MVCs collected every 2 min were used to adjust the number of repetitions in each set in an attempt to decrease the MVC force at a roughly linear rate. Subjects were encouraged to pull to their maximum ability during each MVC, and were allowed to stand and stretch between sets if time permitted. An MVC was also performed at the end of the fatigue protocol to quantify the subjects' level of fatigue. Subjects were fatigued to 68.3 ± 7.2% of their unfatigued lumbar extensor MVC. Once the fatigue protocol was complete, the harness was removed prior to the JMS measurements.

The angular position of the Biodex arm was sampled at 1000 Hz, low-pass filtered at 10 Hz (fourth Order Butterworth filter), and down-sampled to 100 Hz. JMS was quantified as the angular displacement of the Biodex arm (°) between its initial position and its final position after the subject stopped movement. A minimum JMS score of 0.3° was used [24,25] to exclude the possibility that any subject was able to sense motion by the vibration associated with the start of the Biodex motor despite the masking vibration from the hand-held massager. After visually inspecting the data, one subject who consistently performed under this minimum score was removed from the dataset. It has been shown that threshold for perception of passive movement was not dependent on the direction of movement [7]. Comparison of JMS scores for plantar flexion and dorsiflexion from this study also showed no dependence on direction. Thus, the three unfatigued trials in each direction were averaged, and then averaged across directions to produce one JMS score for each unfatigued CAP condition. Since only one trial was collected in each direction following fatigue, the two directions were averaged together to produce one JMS score for each fatigued CAP condition.

Prior to the statistical analysis, a standard square root transformation was necessary to obtain a normal distribution. To determine the effects of fatigue and CAP on JMS, a two-way repeated measures ANOVA was used. The independent variables for this analysis were fatigue condition (unfatigued or fatigued) and CAP condition (no CAP, CAP), and the dependent variable was the transformed average JMS measure. A significance level of $p < 0.05$ was used for all statistical tests.

Both lumbar extensor fatigue and CAP impaired ankle JMS (Fig. 2). Fatigue induced a 14.0 ± 20.6% increase in JMS score ($p < 0.05$) and CAP induced a 22.1 ± 28.8% increase in JMS score ($p < 0.05$). There was no interaction effect of fatigue and CAP on JMS ($p > 0.05$).

The JMS scores found in this study (1.3 ± 0.9°) are comparable to those from similar studies. Konradsen [20] reported threshold levels of joint movement at the ankle typically less than 2°. Using a slightly different experimental paradigm, Clark et al. [5] reported that subjects were able to detect a 1.75° movement at the ankle with 70% success. Fitzpatrick and McCloskey [9] reported much smaller thresholds for

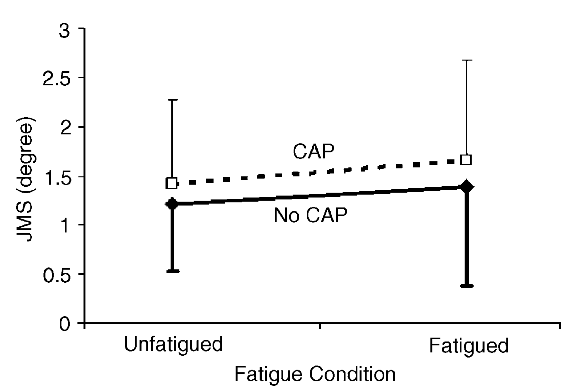

Fig. 2. Mean ± S.D. JMS scores for unfatigued and fatigued condition with and without CAP. The positive slope of both lines illustrates a loss of JMS with fatigue, and the vertical separation of the lines indicates a loss of JMS with CAP.

detection of motion at the ankle—less than 0.2°. However, unlike the present study, subjects in their study stood upright, supported the weight of the body, and used both ankles simultaneously. These differences likely contributed to the smaller values reported.

Impaired joint proprioception at the same joint where fatigue was induced has been reported for numerous joints [2,4,22,34]. Joint position and motion is sensed through various mechanoreceptors, including Golgi tendon organs, muscle spindles, and cutaneous receptors [10]. Several reports have demonstrated that muscle spindle and Golgi tendon organ activity may be decreased with fatigue [14,21]. Similarly, Hiemstra et al. [17] outlined a fatigue-mediated alteration in joint proprioception, pointing to changes in afferent output from joint and muscle receptors as the cause for impairment. These studies provide a seemingly valid physiological explanation for fatigue-induced loss of proprioceptive acuity when fatigue is induced in muscles acting at the joint of interest. However, the loss of proprioceptive acuity when fatigue is induced in muscles not acting at the joint of interest, as reported here, is not as intuitive.

One possible explanation is that lumbar extensor fatigue disrupted the central processing of proprioceptive signals [26]. Gandevia [12] argues that muscle fatigue is the product of both peripheral and central causes; that is, human muscle fatigue does not simply reside at the muscle. Peripheral factors include metabolic changes that directly attenuate contractile function [40]. In addition, there are a number of central changes that occur during fatigue and affect, among other things, proprioception. Sharpe et al. [33] reported changes in proprioception at the elbow resulting from fatigue at either the ipsilateral or contralateral elbow. In an attempt to explain changes in proprioception with contralateral elbow fatigue, they hypothesized that the proprioceptive signals remained unchanged, but the central processing of these signals suffered from fatigue induced changes. In the present study, it is possible that lumbar extensor fatigue, though localized, induced central fatigue which contributed to a general decrease in processing of proprioceptive signals and thus a decrease in proprioception.

The ankle musculature and the lumbar extensors are components of postural control, and like other physiological systems (e.g., the metabolic and cardiovascular systems; [19]) posture status is processed centrally based on a variety of sensory inputs. Therefore, during fatigue, discharges from muscle spindles, tendon organs and small diameter afferents all provide status inputs [12]. For example, Group III and IV afferents that respond to local metabolic and biochemical signals from fatigued muscles may not only inhibit Group 1a input at the spinal level, but also provide feedback to higher centers to alter descending drive [12]. This may be reflected in the increased sense of effort to continue producing the desired contractile force that characterizes central fatigue [12,30]. If the fatigue source originates in a postural component, the "fatigue" feedback may also modify proprioceptive and other input signals from other postural components, perhaps to indicate to the higher centers that postural control is in jeopardy. Our data indicate that central input from a fatigued postural control component may represent a critical mechanism in loss of body postural control. This suggests a process hierarchy, one in which input from fatigued muscles dominates input from non-fatigued muscles. Although speculative, this hierarchy may be more evident in postural control than in other physiological systems, and may explain why local lumbar fatigue blunts the proprioceptive input from the ankle that leads to increased postural sway, and perhaps ultimately loss of balance and injury.

Contrary to previous reports [1,42], CAP impaired proprioceptive acuity. One reason for these conflicting results may be related to differences in measures of proprioception. Two previous studies investigating circumferential joint pressure and proprioceptive acuity [1,42] both used measures of joint position sense (JPS) rather than JMS. JPS is typically measured by determining the error associated with active or passive reproduction of a joint angle [7]. Grob et al. [15] reported a low correlation between JPS and JMS measures which suggests these measures reflect different aspects of joint proprioception. Interestingly, studies investigating the effect of taping and bracing on proprioceptive acuity have similar findings. Hubbard and Kaminski [18] reported a decrease in ankle JMS with ankle bracing, while Heit et al. [16] and Feuerbach et al. [8] reported improvements in JPS with ankle taping and bracing. Pacinian corpuscles in the skin are phasic mechanoreceptors that are sensitive to transient changes in skin pressure. Due to their viscoelastic properties, they are insensitive to tonic or slow-acting changes in skin pressure. If CAP augments sensory signals from these receptors, it is possible that JMS will not benefit from CAP because sensing the slow angular velocities used during JMS testing are poorly sensed by these receptors. However, JPS may still benefit from CAP because the joint angular velocities are likely to be much faster that those used here. Another possible reason for the conflicting results between studies may be differences in experimental protocols. Studies investigating the effect of taping and bracing on ankle proprioception during a non-weight bearing position have found a loss of proprioceptive acuity [18,31], while similar studies employing a weight-bearing position have found an improvement in proprioceptive acuity [8,16,32,42]. This suggests that a weight-bearing stance could change the effects of taping, bracing, and CAP on proprioception.

Three limitations of this study warrant discussion. First, we assumed that the ankle musculature was not fatigued during the lumbar extensor fatigue protocol. Our experience and subject verbal feedback indicated that the ankles were minimally exerted during the fatigue protocol, so we feel there is little chance for ankle fatigue to have occurred. Second, we assumed that the activation level of the plantar flexors and dorsiflexors during JMS testing was constant across all experimental conditions. This is important because proprioceptive acuity is affected by muscle-activation levels [9].

Although subject positions on the Biodex were identical for all experimental conditions, we cannot rule this out because fatigue has been shown to affect activation levels of muscles that are remote to the fatigued muscles [12,37]. Third, it is unclear if the 14.0% loss of ankle JMS with lumbar extensor fatigue is clinically significant.

In conclusion, muscle fatigue of the lumbar extensors decreased ankle JMS. Our results also indicated that the application of CAP decreased ankle JMS. Although this provides a convenient explanation for the previously reported increase in postural sway with lumbar extensor fatigue, this finding is not intuitive. Future studies are needed to better understand the relationship between muscle fatigue, ankle JMS, and balance.

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