THE CROSS-OVER INFLUENCE OF UNILATERAL LOWER LIMB MUSCULAR FATIGUE ON POSTURAL CONTROL

by

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ABSTRACT

The purpose of this study was to examine the cross-over influence of lower limb fatigue on postural control. Young, healthy TCU students (N=20; ages 20.6 ± 1.0 years old; 10 males, 10 females) participated in the study. The study involved six single-legged balance tasks performed on a force plate conducted before and after a fatiguing exercise that included four sets of one-minute single-legged squats on the dominant leg with 30 seconds of rest in between each set. Postural control data, medial-lateral (ML) and anterior-posterior (AP) sway, were collected on the force plate during the balance tasks: right leg eyes open, left leg eyes open, right leg eyes closed, left leg eyes closed, right leg on foam surface, and left leg on foam surface. Data were analyzed with the linear variable of standard deviation (SDML, SDAP) and the nonlinear variable of detrended fluctuation analysis (dfaML, dfaAP). The results lacked significant differences ($p>0.05$) for crossover fatigue effects on both the non-exercised and exercised legs, which exhibited similar levels of postural sway between pre- and post-fatigue balance tests. Results indicated some participants increased while some decreased postural sway post-fatigue exercise. In conclusion, the single-legged squat task may have lacked an appropriate level of duration or intensity to cause a significant effect of central fatigue on the nervous system. The findings underscore the need to better understand how a specific fatiguing task during unilateral rehabilitation may alter postural control.

INTRODUCTION

Postural control and balance are essential components to maintaining upright stances and executing daily activities. Fatigue can negatively impact the ability of the muscular and sensory systems relating to the maintenance of postural control. Understanding elements of balance and cross-over fatigue, which can occur in homologous contralateral muscles on a non-exercised limb, may provide new insights to physical training, preventative measures for loss of balance, and rehabilitation for unilateral injuries, diseases, or paralysis. The effects of cross-over fatigue primarily derive from upper limbs movements, while the degree to which cross-over fatigue affects lower limb motor tasks remains unclear.

Muscular fatigue

Muscular fatigue is defined as the failure to exert the required force or power (Danion et al., 2001). Fatigue occurs when physiological impairments impact cognition, proprioception, and muscular activity during physical performance (Abd-Elfattah et al., 2015). Two physiological aspects of fatigue are peripheral and central mechanisms. Peripheral fatigue is the decrease in muscular force due to changes in the skeletal muscle at the level of or distal to the neuromuscular junction while central fatigue is the reduction of voluntary activation due to changes that are independent of skeletal muscle contractions (Gandevia, 2001; St. Clair Gibson & Noakes, 2004). Theories of central fatigue support the idea that neural changes occur as a chain from higher central nervous system levels descending to muscle fibers. A decrease in neural drive throughout the nervous system chain levels due to fatigue or injury leads to reduced force production through a lack of motor unit recruitment. The decreased response functions as a subconscious protective mechanism to reduce force output during excessive effort when failure of the motor cortex or other inputs at the spinal level occur (Gandevia, 2001). A comprehensive understanding of muscular fatigue is necessary to determine its effects on performance, risk of injury, or loss of balance.

Muscular fatigue and postural control

Fatigue is one of the many factors that can impair balance by impacting postural control. Muscle fatigue disrupts afferent feedback of proprioceptive and sensory mechanisms, thus slowing the ability to use effective compensatory movements in posture (Arora et al., 2015). The level of fatigue is dependent on the task performance, force, voluntary versus electrical stimulation, isometric versus dynamic exercise, and sustained versus intermittent activities (Allman & Rice, 2002). Exhaustion from physical activities deteriorates sensorimotor input and integration with the muscular system (Bizid et al., 2009). Fatigued muscles of the knee, hip, and ankle create significant decreases in stabilization during both double-legged and single-legged stances causing reduced postural control (Gribble & Hertel, 2004). Effects of fatigue are a risk factor for musculoskeletal injuries due to the altered recruitment patterns when maintaining postural control (Murphy et al., 2003). Therefore, the present aim works to understand the effects of fatigue on single-legged postural control.

Postural control provides successful and efficient performance of everyday tasks, relying upon sensory input systems of vision, vestibular, and proprioception. Therefore, removing visual input or absence of lower limb proprioception will result in decreased postural stability (Collins & De Luca, 1995; Soleimanifar et al., 2012). Postural control is measured by the displacement of the center of mass, center of foot pressure, or body segment activity. The smaller displacement of mass or pressure correlates with better postural control (Paillard, 2020). Therefore, when assessing postural control after fatiguing motor tasks, increased center of pressure and sway velocity is expected (Boyas et al., 2013).

Single-legged stance is a common position used to evaluate balance when challenging posture by narrowing the base of support compared to a double-legged stance. The muscles of the lower leg control postural stances and changes in muscle activity depending on the surface properties (Strøm et al., 2016). For example, standing on an unstable surface, like a foam pad or BOSU ball, resulted in increased muscle activity in the lower limbs during eyes open and closed conditions (Braun Ferreira et al., 2011). Multiple studies have displayed greater effects of fatigued proximal muscles only around the hip and knee to increase medio-lateral sway, while fatigued ankle, hip, and knee muscles resulted only in an increased antero-posterior sway. The former muscles are recognized as greater contributing muscles to maintain upright stance than the distal muscles (Bisson et al., 2011).

Single-legged postural control has contradictory findings comparing stances between dominant and non-dominant legs. Environmental contexts and physiological states can influence the results between the two limbs. Limb dominance is likely context-dependent based on sports, repeated motor tasks, and support of body mass during other tasks (Paillard & Noé, 2020). The dominant leg is often viewed as the kicking leg, with preference over one lower limb compared to the other to perform one-sided tasks. Limb dominance reflects asymmetries in motor control neural circuits in both upper and lower limbs. Compared to upper limb dominance, lower limbs are more likely to be task dependent during weight bearing, locomotion, or dynamic tasks. COP variables used in measuring unipedal postural control did not have an effect on leg dominance, although visual feedback made a difference since it is also processed asymmetrically in the brain (Promsri et al., 2020).

Cross-Education

The idea of cross-education proposes that the ipsilateral training of one limb produces significant strength benefits to the homologous muscles of the contralateral limb (Joanne Munn et al., 2005). Cross-education, or cross-over training, can be beneficial for muscle sparing during immobilization of a limb and has been observed in skill, strength, learning, and ballistic motor activities (Andrushko et al., 2018). Unilateral training and rehabilitation have been shown to be moderately effective in post-stroke patients for motor function recovery, strength, and gait improvements in the contralateral limb (Ehrensberger et al., 2016). Mechanisms for cross-over effects have been determined to be from other causes that are not related to muscle morphology. Ipsilateral training does not result in contralateral tangible contractions, therefore, no muscle hypertrophy is evident (Paillard, 2020). Other proposed causes include neural activation of the contralateral voluntary motor cortex or spinal mechanisms. Cross-over effects have been identified in upper limbs, but there is conflicting evidence for the effects on lower limbs. Unilateral training has been understood to produce cross education effects in contralateral limbs relating to postural control (Paillard, 2020). Effects have been observed in healthy and pathological subjects.

Many studies have observed the contralateral effects of upper body limbs, which are guided to perform single limb movements such as reaching and grasping (Magnus et al., 2010; J. Munn et al., 2004; Pearce et al., 2013). However, lower limb movements typically involve synchronized movements such as locomotion and balance where cross-over effects may be more pronounced. Locomotion requires the nervous system to control sequences of both lower limbs through detailed commands and muscle functions, thus emphasizing functional importance of cross-over effects (Rattey et al., 2006). Although lower limb training has produced enhanced effects on the contralateral limb, results from other studies are unclear if cross-over effects are similar for muscle fatigue. Executing motor tasks on the contralateral limb may be beneficial for athletics or rehabilitation where performance can be enhanced through training of the homologous opposing limb or preventing atrophy from immobilization.

Meta-analyses estimate the contralateral effects as an absolute gain of ~8%-12% relative to the trained limb, however they are measured as an attenuation to expected losses without the unilateral trained limb. Current studies have focused on the contralateral training effects in the context of unilateral injuries or trauma to improve contralateral rehabilitation or training techniques. Studies conducted on balance training in various postural conditions displayed improved ipsilateral and contralateral single-legged postural control after multiple sessions per week for 4-8 weeks (Paillard, 2020). Effects of resistance training on cross-education effects of postural control remain unclear compared to multi-joint, dynamic exercise training. Contralateral training is useful for enhancement or preservation of single-legged postural abilities and prevention of new injury risks (Paillard, 2020).

Cross-over fatigue

Muscle fatigue has been a widely investigated topic, although data is lacking with cross-over fatigue effects (Doix et al., 2013). Cross-over fatigue effects are demonstrated by a decrease in force production, torque production, and maximum voluntary contraction (MVC) of the non-exercised limb of the contralateral homologous muscle after a fatiguing exercise (Miller et al., 2020). Previous research has shown the effects of local fatigue occurring in one limb leading to contralateral decreases in force of the homologous muscles in non-fatigued limbs (Arora et al., 2015; Doix et al., 2013). Other studies have determined cross-over fatigue in upper limbs to be the result of decreasing drive from the motor cortex after a fatiguing voluntary contraction on the contralateral side (Doix et al., 2013). Cross-over fatigue effects are determined to be centrally driven by neural factors that produce rapid force (Aagaard et al., 2002). An increased degree of effort can also be felt by other activities other than the source of fatigue, such as feeling fatigued after intense physical or mental work or overall tired after a sporting event (Zijdewind et al., 1998).

Cross-over fatigue effects have resulted in reduced voluntary muscle activation and decreased force production. Research has demonstrated sex differences in contralateral cross-over fatigue in one study with males having a greater reduction in force production compared to women by 13% and a greater reduction in force in the contralateral limb, 9% in males and 3% in females, following sustained contractions of the dominant limb (Martin & Rattey, 2007). Cross-over effects were accentuated as postural task difficulty increased and relative length of the fatigue tasks to induce alterations of postural control and motor output (Arora et al., 2015). Therefore, duration of a task will likely impact the single-legged postural control of the contralateral limb. However, it remains unclear the specific required intensity and duration to evoke cross-over effects in the contralateral limb. One study concluded that MVC around 10-30% for less than 16 second bouts did not induce sufficient fatigue effects. In the current study, participants performed four bouts of one minute single-legged squats in order for the duration to induce effects of postural control during balance. Evidence suggests fatiguing exercises disturb contralateral postural control during single-legged stances, although effects of carrying out postural control with cross-over effects have not been determined (Paillard, 2020).

METHODS AND MATERIALS

Participants

A total of 20 individuals (10 male, 10 female: age = 20.6 ± 1.0 years old, height = 172.9 ± 8.6 cm, weight = 68.8 ± 11.5 kg) participated in this study. Participants were healthy young adults at Texas Christian University, with no current lower extremity injuries within the past year, normal or corrected-to-normal vision, no known balance disorder, and no neuromuscular disorder or impairment. Individuals were required to review and sign an informed consent form prior to participation. All procedures were approved by the Texas Christian University Institutional Review Board.

Equipment and Materials

Postural control data were collected with a force place (OR6-7, AMTI, Watertown, MA) that recorded forces and moment data. Data obtained from the force plate were used to compute center of pressure (COP) trajectories in the anterior-posterior and medial-lateral directions during each balance task. A wooden box (height: 50 cm) was used to perform the single-legged squats. Standing in an elevated position allowed participants to relax the non-exercising leg along the side of the box during the fatiguing exercise (Figure 1).

Figure 1. Participant demonstrates squat fatiguing exercise by fatiguing the dominant leg and non-exercising leg relaxed on the side of the elevated wooden box.

Procedures

After completing the consent procedures, each participant completed the Waterloo Footedness Questionnaire to determine dominant leg. Participants removed socks and shoes to eliminate any effects that shoe types might have on balance. The researcher recited instructions before each task to minimize physical risks and confusion. Participants completed a series of pre- and post-fatigue balance tasks on the force plate. All trials consisted of single-legged standing with variations of the right and left foot, eyes open and eyes closed, and stable and unstable surface types (Figure 2). The researcher randomized the order of balance tasks to prevent order effects. Task randomization was completed before data collection and the order was used for all subjects. Each task was performed for 30 seconds with approximately 30 seconds of rest before the next task. During the balance tasks, participants were instructed to maintain an upright stance with hands on hips, to hold the non-weightbearing leg relaxed in a 90-degree knee flexion position, and to maintain a forward gaze at a target located approximately one meter in front of them (Figure 3). Failed attempts were considered by placement of the non-weight bearing leg on the ground or losing contact with the force plate. Trials were repeated up to two times following failed attempts.

Following the pre-fatigue balance tasks, individuals put shoes on to complete the fatiguing exercise on the dominant leg. The fatiguing protocol included four bouts of single-legged squats for one minute with 30 seconds of rest given between each bout. Single-legged squats were performed in an elevated position on top of the wooden box (Figure 1). The set up was designed to fatigue the dominant limb while maintaining minimal activity of the non-dominant limb. The non-dominant limb remained at the side of the box in order to keep the whole leg in a relaxed position and minimize contraction of lower limb muscles and hip flexors.

The researcher demonstrated the correct form of squats before the participant began the exercise task. The box was located near a stable wall in case the participant needed support during a loss of balance, but otherwise were encouraged not to touch the wall during the fatiguing task. Participants were verbally encouraged to maintain the exercise continuously for the minute with the correct form as demonstrated by the researcher. Following the exercise, the participants reported a level of fatigue on their dominant leg on a scale from 1-10 (mean: 6.1 ± 1.3). A score of one represented feeling no fatigue or feeling no effects of exercise whereas a 10 represented the worst fatigue experienced feeling unable to stand anymore. Participants immediately began the post-fatigue balance tasks in the same manner as the pre-fatigue session.

Figure 2. Methods Protocol. The order of randomized balance tasks completed pre- and post-fatiguing protocol.

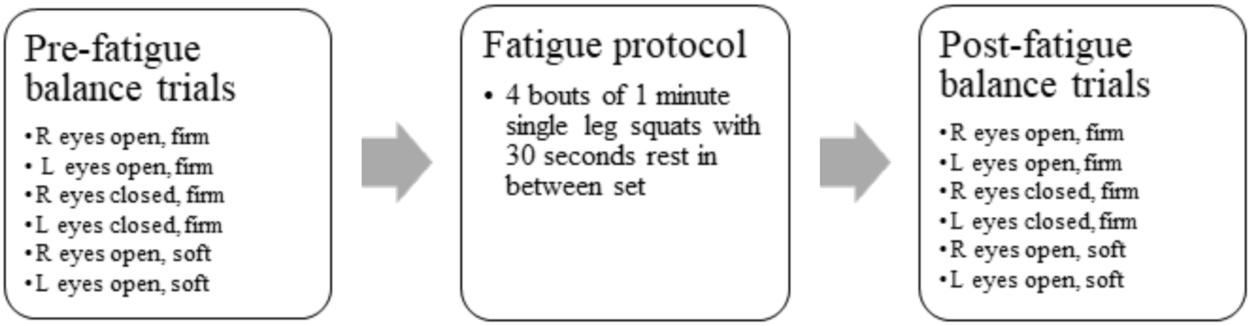

Figure 3. Participant demonstrates proper balance stance with unilateral foot on the center of the force plate, non-weight bearing leg relaxed in 90-degree position, hands resting on hips, and gaze forward at eye height.

Data analysis

Data were exported from Qualisys to Matlab (Mathworks, v. 2019b) where custom code was used to compute COP measurements. To ensure the participant was standing firmly on the force plate during balance tasks the first three and last two seconds were cropped from the collected data. The COP signals were smoothed with a low pass, second order Butterworth filter and a 10-Hz cut-off frequency. Dependent variables of linear COP included the standard deviations in the medial lateral (SDML) and anterior posterior directions (SDAP) and detrended fluctuation of analysis in the medial lateral (dfaML) and anterior posterior directions (dfaAP).

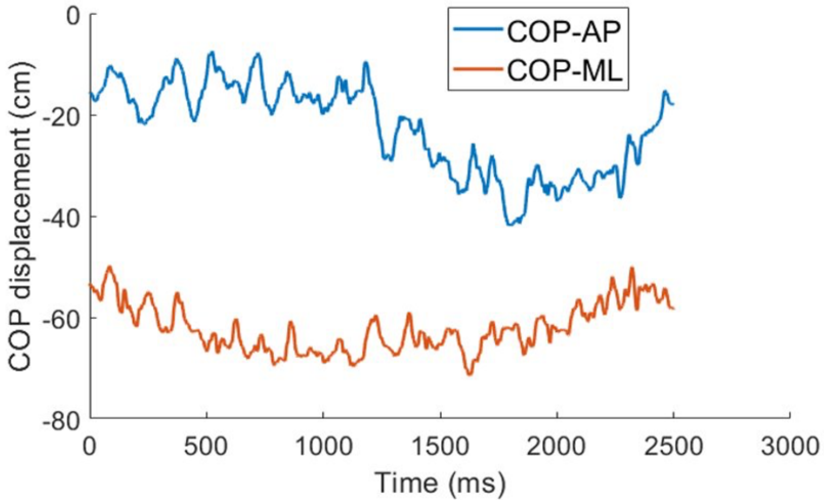

Figure 4. Example graph of COP displacement (cm) from the mean trajectory of unilateral postural control on the force plate in both AP and ML directions.

Statistical Analysis

The dependent variables were analyzed using univariate analysis in SPSS software. Eyes closed data were not analyzed due to participants' inability to maintain balance for the entire 30 second duration of the balance task. Fixed factors in the analysis were pre- and post- fatigue, hard surface, and foam surface. List out the fixed factors (pre/post and hard/soft). Significance level was set at $p<0.05$.

RESULTS

Center of Pressure: Standard Deviations

Standard deviations were measured from the center of pressure trajectories in centimeters. The test conditions of fatigue and surface types did not have significant effects on the SDML of COP trajectory for both the fatigue leg and non-fatigue leg ($p=0.19$, $F=1.73$; Figures 5 and 7). These interactions did not have statistical significance with testing ($p=0.84$, $F=0.04$) nor with surface type ($p=0.56$, $F=0.34$). Testing conditions and surfaces did not result in significant effects on the SDAP of COP trajectory for both the fatigue leg and non-fatigue leg (p=0.80, F=0.07; Figures 6 and 8). These interactions with testing (p=0.95, F=0.00) and surface did not have statistical significance (p=0.30, F=0.72).

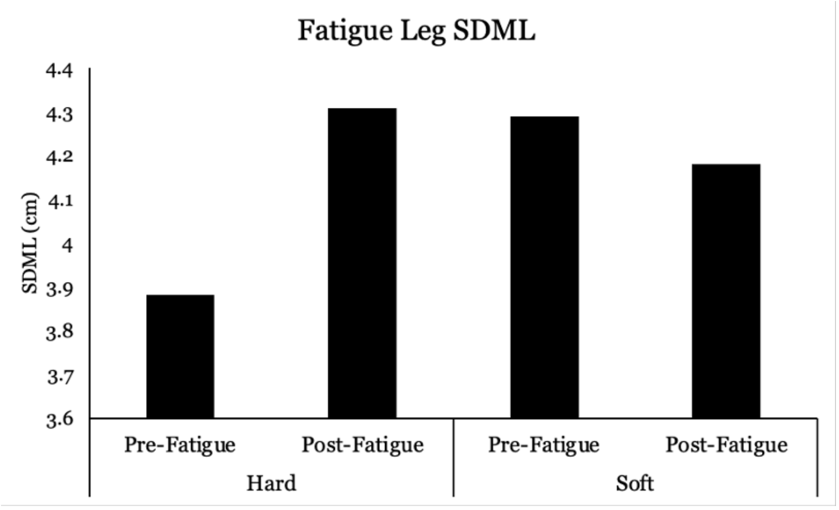

Figure 5. Mean standard deviations (cm) in the ML direction for the fatigue leg.

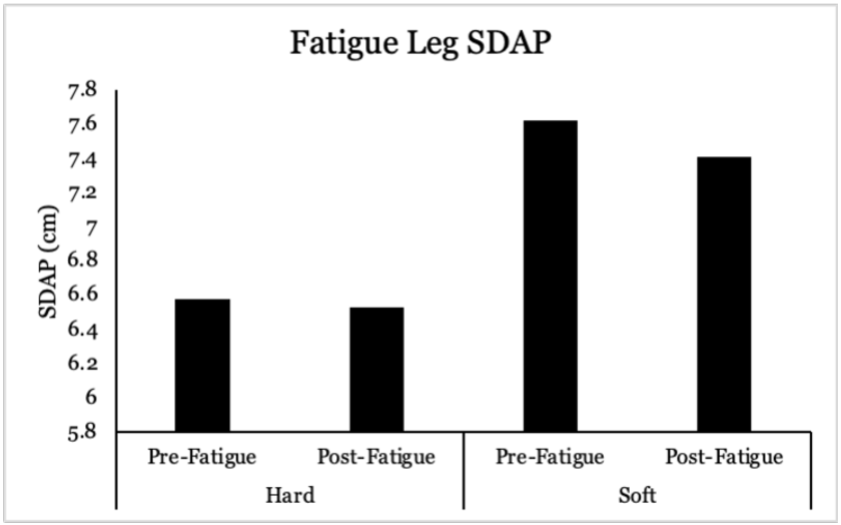

Figure 6. Mean standard deviations (cm) in the AP direction for the fatigue leg.

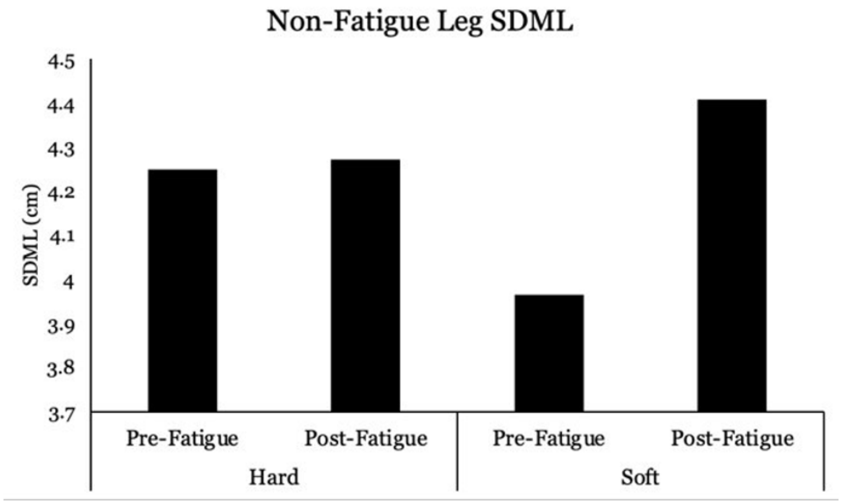

Figure 7. Mean standard deviations (cm) in the ML direction for the non-fatigue leg.

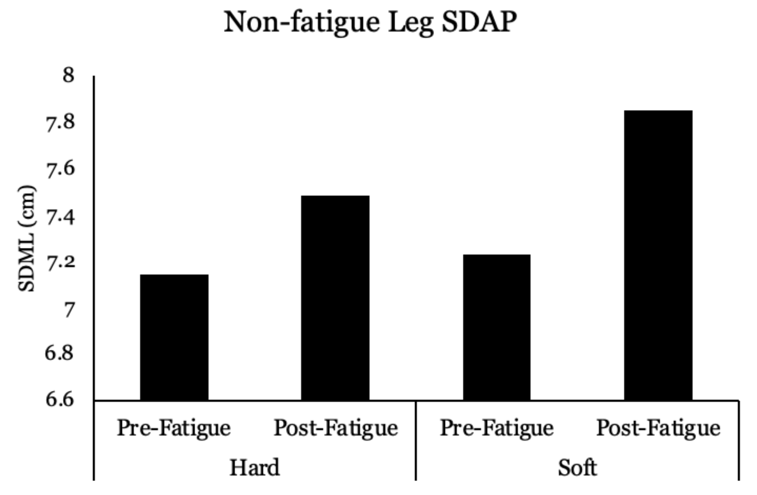

Figure 8. Mean standard deviations (cm) in the AP direction for the non-fatigue leg.

Center of Pressure: Detrended Fluctuations Analysis

Center of pressure was measured with detrended fluctuation of analysis in the medial lateral (dfaML) and anterior posterior (dfaAP) directions, which determines changes in the graph fluctuations of COP. Testing conditions and surface type did not have significant effects on the medial lateral direction (dfaML) of COP trajectory for both the fatigue leg and non-fatigue leg (p=0.38, F=0.77; Figures 10 and 12). These interactions did not have statistical significance with testing (p=0.22, F=1.49) or surface type (p=0.94, F=0.01). Testing conditions and surface type did not have significant effects on the anterior posterior direction (dfaAP) of COP trajectory for both the fatigue leg and non-fatigue leg (p=0.49, F=0.48; Figures 9 and 11). There were not statistical significances with testing (p=0.07, F=3.15) or surface type (p=0.87, F=0.02).

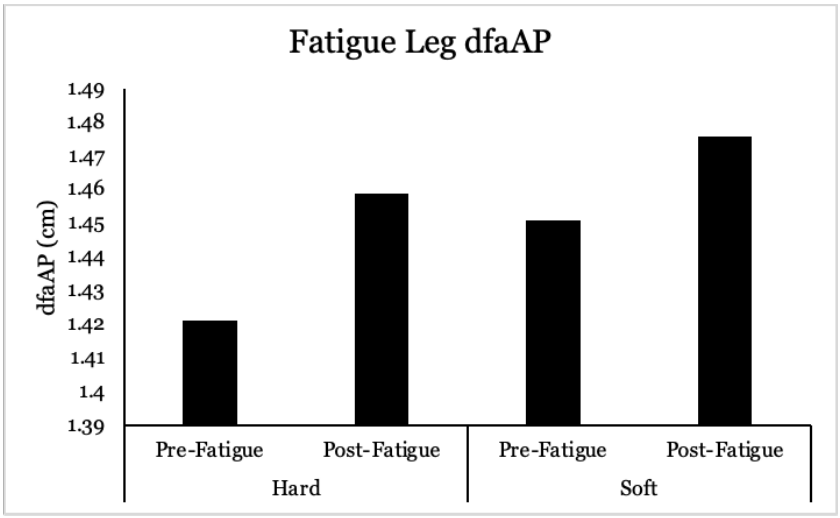

Figure 9. Mean dfa (cm) in the AP direction for the fatigue leg.

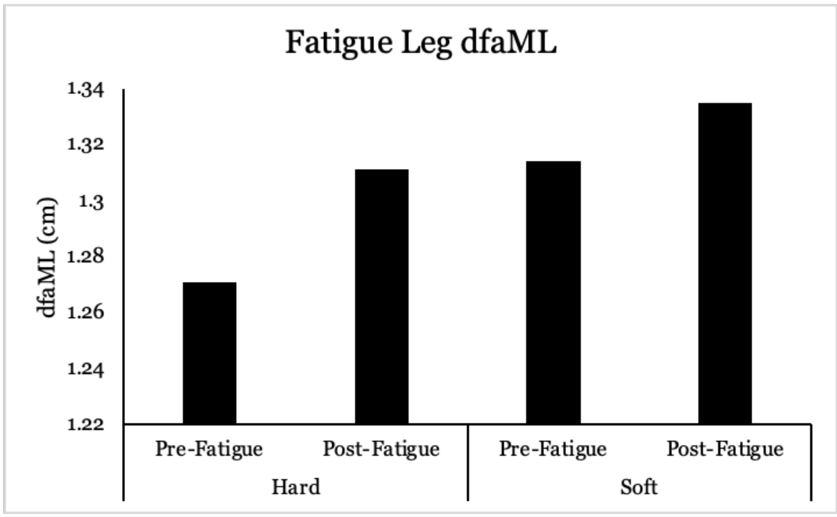

Figure 10. Mean dfa (cm) in the ML direction for the fatigue leg.

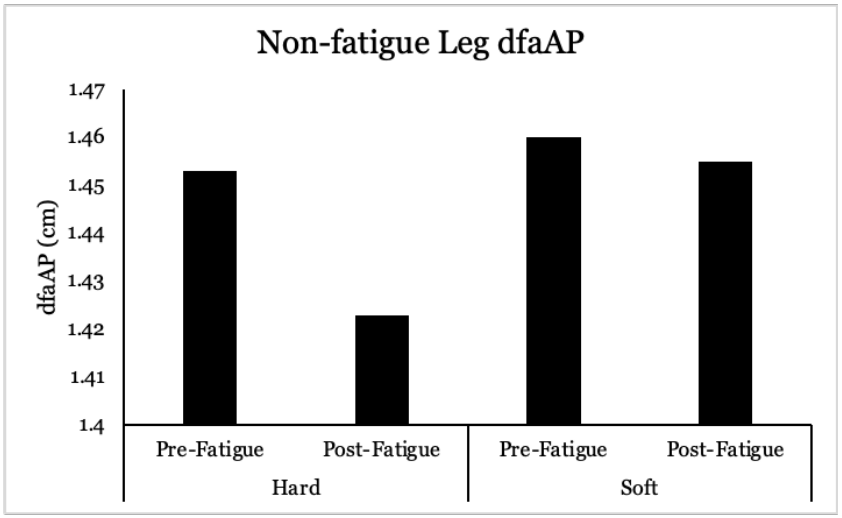

Figure 11. Mean dfa (cm) in the AP direction for the non-fatigue leg.

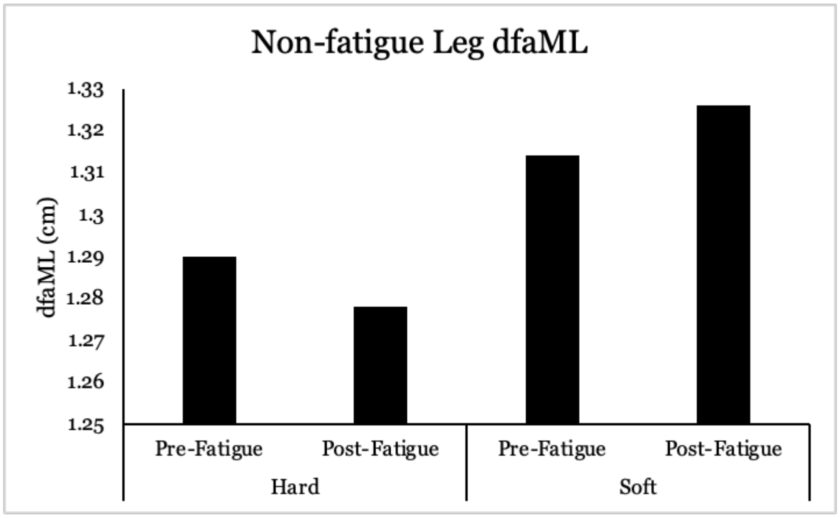

Figure 12. Mean dfa (cm) in the ML direction for the non-fatigue leg.

DISCUSSION

This study examined the impact of postural control on the non-exercised leg after completing a fatiguing exercise. The hypothesis of this study that cross-over fatigue would influence postural control was not supported in that the completion of the fatiguing exercise task did not significantly alter postural sway of the fatigued nor the non-fatigued leg. Although our results did not confirm our expected outcomes, the research aids to understand the types of fatigue that may or may not induce meaningful cross-over effects for postural control sway. The findings may have been attributed to the intensity and duration of the fatiguing exercise.

The fatiguing exercise (single leg squatting) was completed with four sets of one-minute bouts with 30 seconds of rest in between sets. Comparing the findings to previous studies that examined lower limb postural control and fatigue, it can be reasoned that cross-over effects with longer durations have a greater influence on postural sway. For example, maximum voluntary contractions (MVC) set at 10% for a fatiguing exercise completed for a total of 33 minutes led to significant changes in unilateral postural control of the contralateral leg (Paillard, 2020). A similar study on lower limb fatigue used 30% MVC and exercised for collective 3.5 minutes but did not have a significant effect on postural control of the non-exercised leg (Arora, 2015). The single leg task in the current study may not have been a long enough duration to produce CNS stress that affected central fatigue and postural control stances (Frazer et al., 2018). Four minutes of squatting could have been categorized in between local and general fatigue (Paillard, 2010). Therefore, increasing the duration of fatigue might induce stronger cross-over effects of the non-exercised leg.

In addition to fatigue duration and intensity, fatigue and balance task dissimilarities may have produced the lack of cross-over effects. Specifically, different contralateral motor command used in the brain and spinal pathways could vary for the squat task compared to the balance stances (Hortobagyi et al., 2003). Cross-over effects are produced with the homologous contralateral muscle group; therefore, muscle specificity of the fatiguing task and balance are important (Frazer et al., 2018). The squatting task may not be specific enough with muscle contractions similar to the muscles activated during unilateral postural control stance, thus, lacking cross-over effects after fatigue. The fatiguing task in the current study may have produced effects of general fatigue by involving multiple joints of the body with a more dynamic task as compared to a MVC test, lacking a specific muscle group relating to unilateral postural control stances (Paillard, 2020).

Compensation strategies occur during postural control stances and result in differences of upright stances between individuals. Strategies to maintain balance and resist sway may be altered after postural control muscles are fatigued post-exercise, depending on the type of task and degree of fatigue (Paillard, 2010). Fatigue to proximal muscles of the hip and knee cause greater deficits in unilateral stances compared to ankle fatigue (Gribble, 2004; Paillard, 2009). The squat task was performed in the AP plane while the balance tasks were performed using muscles in the AP and ML direction. Because the squatting task emphasized fatigue in the AP direction, balance compensation occurred through a more active role of ML postural control muscles (Harkins et al., 2005; Paillard, 2011). These compensations through coactivation of lower limb muscles may indicate the divergence of participants with both increases and decreases in postural control sway after exercise (Harkins et al., 2005). Figures 13-16 display the difference between pre- and post- fatigue standard deviations in (cm).

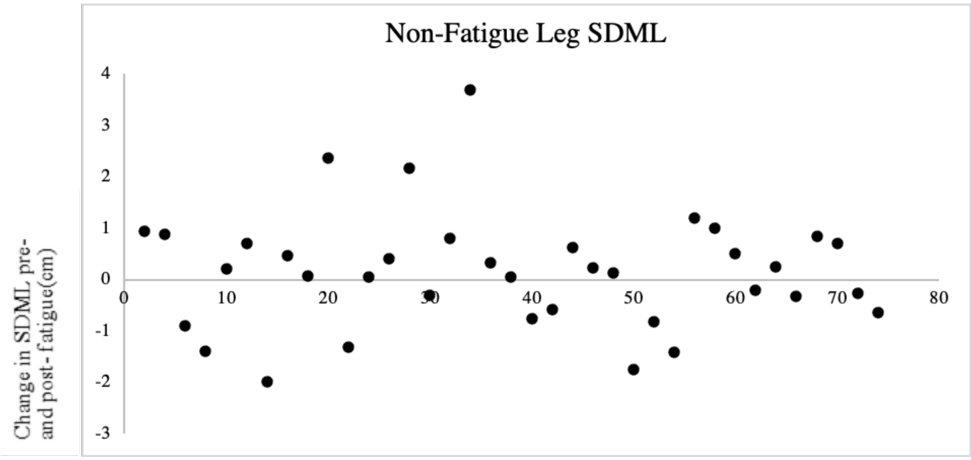

Figure 13. Non-Fatigue leg SDML mean plots of sway changes pre- and post- fatigue.

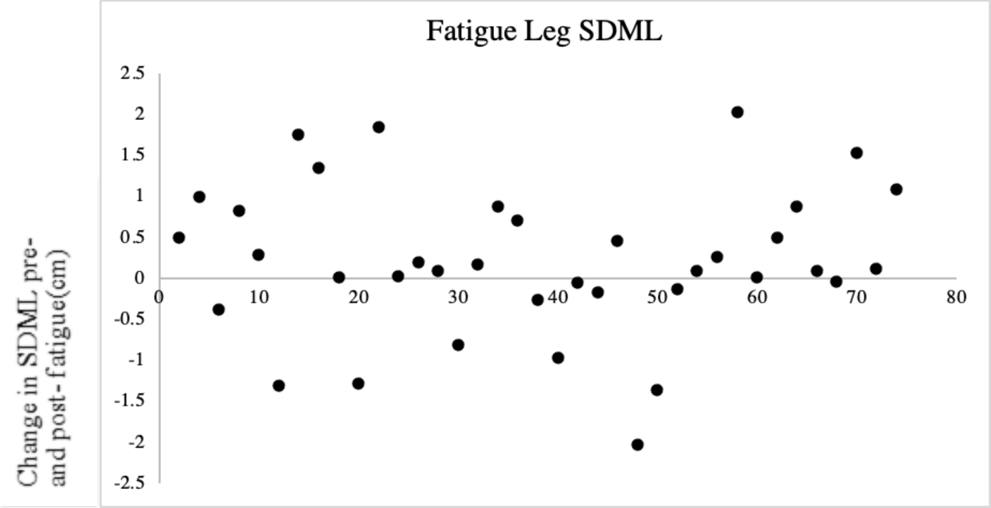

Figure 14. Fatigue leg SDML mean plots of sway changes pre- and post- fatigue.

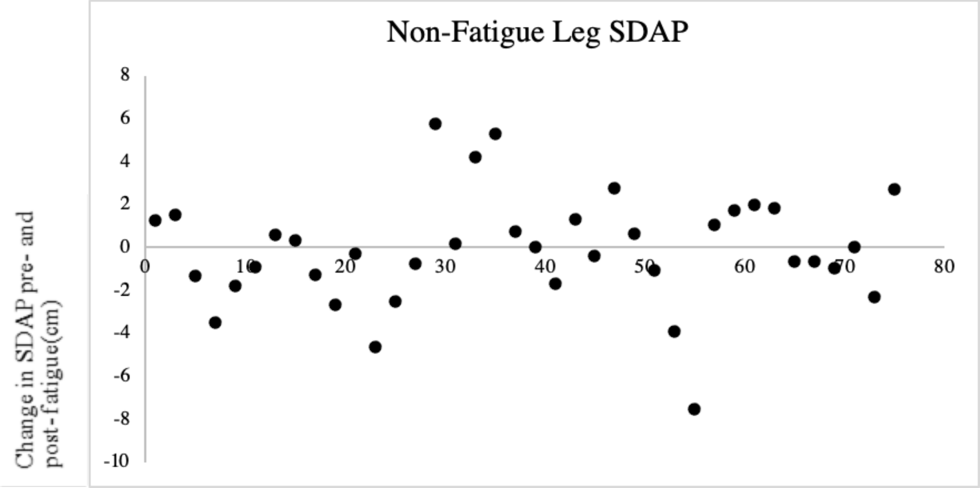

Figure 15. Non-Fatigue leg SDAP mean plots of sway changes pre- and post- fatigue.

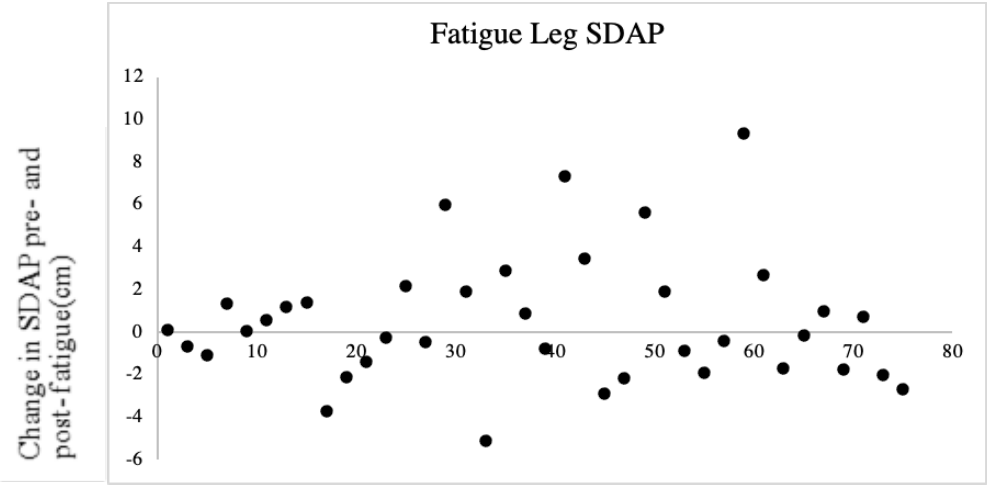

Figure 16. Fatigue leg SDAP mean plots of sway changes pre- and post- fatigue.

A limitation of this study was the small sample size. Additionally, the influence of participants' exercise background on the level of fatigue during the exercise and balance tasks may have limited the significance of cross-over effects seen in this study. Some participants were more fatigued after the four-minute exercise compared to others who were experienced milder degrees of fatigue, as recorded by the fatigue RPE scale. The researcher noticed some individuals who may have participated in aerobic and dance-based workouts compared to other participants who may have focused more on resistance workouts. The previous training and workout exercise experiences could have resulted in the fatiguing task being more tiring to some participants rather than others without the lab controlling for fatigue through quantifiable measures such as MVC.

CONCLUSION

The study results did not support the original hypothesis but lead to a greater understanding of the intensity and duration influence of cross-over fatigue on postural control. Future research should examine the types of fatiguing task that impact postural control while also considering exercise background. Exploring fatiguing exercises of the lower limbs with longer durations and more vigorous intensities will clarify the fatiguing mechanisms that impact postural control of the non-exercised leg. From this research and future studies, impacts of fatigue on postural control help determine benefits of rehabilitation and exercise programs that focus on unilateral limbs.

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