Burnett School of Medicine at TCU

Acute cross-over effects of lower limb muscle fatigue on movement strategies of young adults during upright standing

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Abstract

Research Question: Are there acute cross-over effects of lower limb muscle fatigue on movement strategies of young adults during upright standing?

Introduction and Significance for the Question: Our study made use of three major concepts: the cross-education phenomenon, muscle fatigue, and postural control. The cross-education phenomenon pertained to the effects of training one side of the body to the untrained contralateral or opposite side. Muscle fatigue was the decrease in maximal force as a response to contractile activity. Lastly, postural control was the ability that allowed one to maintain upright standing. Looking at these three components—the cross-education phenomenon, muscle fatigue, and postural control—that have been studied over the last century, we developed a research idea that used the influence these three had on each other. Our research generated a quantitative analysis of the cross-educational phenomenon on postural control by observing contralateral muscle fatigue.

Materials and Methods: Twenty individuals (17 males, 3 females) were enrolled in the study. Participants were healthy young adults, with no lower extremity injuries, normal or corrected-to-normal vision, no known balance disorder, and no neuromuscular disorder or impairment. Postural control data was collected with a force plate (OR6-7, AMTI, Advanced Mechanical Technology, Inc., Watertown, MA) that recorded forces and moment data. Participants performed pre- and post-fatigue balance assessments on a force plate, including single-legged standing with variations of the dominant and nondominant leg and stable and unstable surface types. Following the initial balance assessment, a fatigue task of single-leg standing calf raises was performed until exhaustion. Data from the pre-fatigue balance task and post-fatigue balance task were analyzed and compared.

Results: The Coefficient of Variation in the Anterior-Posterior (CVAP) direction for the fatigued Dominant Leg exhibits steep variability, indicating significant sway during the post-fatigue balance task, as expected. The CVAP for the unfatigued Nondominant Leg also shows an increase in variability, though not as steep, which can be attributed to the crossover effect ($p=0.043$).

Conclusion: Acute fatigability on one of the lower limbs in our subjects influenced contralateral postural stability and control during upright standing. This was supported objectively by measurements of the muscle activity from the force plate device. As for impact, we increased our understanding of postural control training through cross-education and provided additional evidence via objective data. Future work can include increased power, more diverse subjects, or, or other limbs. We hope that our study has provided valuable insights for various applications, such as physical rehabilitation or performance training.

Research Question

Are there acute crossover effects of lower limb muscle fatigue on movement strategies of young adults during upright standing?

Hypothesis: We hypothesize that inducing a local fatigue to a lower limb muscle will induce a significant fatiguing effect on the homologous contralateral limb muscle.

Introduction, Significance, and Rationale

Introduction

Training one side of the body whereby it produces effects (like increased strength, flexibility, etc.) on that same side is known as ipsilateral effects. For example, performing bicep curls with a dumbbell on the dominant side of the body will produce contraction, fatigue, and/or hypertrophy on the ipsilateral side of the body. On the other hand (no pun intended), when a positive effect is realized on the opposite, untrained limb it is referred to as the contralateral effect.

I. Cross-education Phenomenon

Cross-education phenomenon is a theory that dates as far back as 1898 in which it was first coined by Walter Davis in his work [1]. (Nonetheless, Davis alludes to it being first observed by H F Weber [2].) Since then, the cross-education phenomenon has been referred to by various similar terms, such as contralateral training, contralateral learning, cross-over effect, cross-exercise, cross-transfer, or inter-limb transfer [3]. Regardless of the name, the cross-education phenomenon pertains to the effects of training one side of the body to the untrained contralateral or opposite side [1]. Back in 1899, Walter Davis did experiments on cross-education in relation to strength, speed, and accuracy. Cross-education experiments have since been expanding in various other aspects of physiology:

I.A. Cross-education in Upper Extremity Strength Training

A study had 115 participants randomly assigned to a control group or to one of the four training groups that performed elbow flexion contractions [4]. These groups include: 1) one set at low speed, 2) one set at high speed, 3) three sets at low speed, or 4) three sets at high speed. Participants in these training groups trained 3 times per week for 6 weeks total with a maximum load for 6 to 8 repetitions while participants in the control group attended sessions but did not exercise. The study concludes that training one limb for three sets produced small increases in strength to the contralateral (untrained) limb [5].

I.B. Cross-education in Upper Extremity Muscle Size Preservation

In a one-month study period, sixteen healthy individuals volunteered to have their nondominant forearm immobilized with a cast [6]. These individuals were then randomly assigned to either a resistance-training group or a control group. The resistance-training group performed eccentric wrist flexion movement 3 times per week on their uncasted forearm while the control group did not. Pre- and post- testing involved taking measurements of muscle thickness (via ultrasound) and forearm muscle cross-sectional area (via peripheral quantitative computed tomography) in both forearms.

The forearm flexors' muscle thickness measurements showed changes in both casted (immobilized) and uncasted forearms. For the casted (immobilized) forearm, the control group had a –3.2% change while the resistance-training group had a 2.8% change. For the uncasted forearm, the control group had a –3.7% change while the resistance-training group had a 7.1% change.

The experiment objectively showed that muscle thickness and muscle cross-sectional area were preserved in the immobilized limb for the individuals who were in the resistance-training group. This preservation of size was only limited to the homologous muscles that were involved in the movement.

I.C. Cross-education in Hip Flexor Stretching

In a research involving static and dynamic stretching, the contralateral non-stretched hip flexors showed increased range of motion (ROM) [7]. Its ROM static stretching increased by 5.7% (P-value = 0.02; Effective Size: 0.68), whereas its ROM dynamic stretching increased by 8.4% (P = 0.005; ES: 0.89). The research showed that unilateral static stretching and dynamic stretching augment contralateral limb ROM likely via an increase in stretch tolerance.

I.D. Cross-education in Speed of Voluntary Effort

In Walter Davis' published work in 1899, he measured the speed of his six subjects in tapping a tap counter using the left index finger, the right index finger, the left great toe, and the right great toe [1]. Then for 2 weeks, only the right great toe of the subjects was trained daily. After two weeks elapsed, he had his subjects tap the tap counter again using each of their four digits (left and right index fingers and left and right great toes). The left index finger increased in speed by 28%, the right index finger by 20%, the left great toe by 30%, and the right great toe (the digit practiced for two weeks) by 31%. He concluded that the right great toe being practiced daily influenced the other three digits to gain similar speed increases.

I.E. Cross-education in Foam Rolling and Static Stretching on Hamstring Flexibility and Strength

Ten sets of 30-second self-administered foam rolling and static stretching were performed on the dominant hamstring muscles of 23 participants [8]. The research found that both interventions significantly increased the contralateral hip-flexion passive range of motion (ROM). The post-ROM value was significantly greater (P = .03) for the static stretching (mean ± SE = 73.5° ± 4.7°) compared to the self-administered foam rolling (mean ± SE = 70.3° ± 4.5°). It also found increased contralateral hamstring stretch with main effects for time (P = .03) and intervention (P = .02). The study concludes that the increased contralateral hip-flexion passive ROM was likely due to the enhanced stretch tolerance, whereas strength performance responses might be likely due to neural mechanisms different from the stretch tolerance.

Looking at these five studies above, we can see that there is cross-education in various physiological aspects between limbs, regardless if it is upper extremity or lower extremity. This leads us to ask if cross-education can be seen in movement strategies and postural control.

II. Muscle Fatigue

Muscle fatigue is the decrease in maximal force as a response to contractile activity [5]. It can be described in various ways, such as central vs peripheral or global vs local.

II.A. Central Fatigue vs Peripheral Fatigue

Muscle fatigue can be described as either central or peripheral. Central fatigue is fatigue that originates at the central nervous system or CNS affecting the neural drive of the muscle negatively. On the other hand, peripheral fatigue involves fatigue outside of the CNS (i.e, outside the brain and spinal cord), and is produced by changes by motor pathways leading to the neuromuscular junction [5].

II.B. Global (Whole Body) Fatigue vs Local Fatigue

Fatigue can also be described as global (whole body) fatigue or local fatigue. Global fatigue is fatigue of the whole body. On the other hand, local fatigue is fatigue that is limited to a local muscle or part of the body. An example of the former is the fatigue experienced while doing compound movements, such as deadlifts, whereas an example of the latter is the fatigue experienced doing a bicep curl that is isolated to one arm.

II.C. Non-local muscle fatigue

Non-local muscle fatigue (NLMF) is described as muscle performance impairments in a remote non-exercised or contralateral muscle group following a fatiguing task of a different muscle group [9]. For example, if exercising the right calf muscle by itself produced fatigue on the left calf muscle, this fatigue experienced by the left calf muscle can be described as a non-local muscle fatigue.

III. Postural Control

Postural control is the ability to control one's body position in space for stability and orientation [10]. Simply put, it is the ability to be able to maintain upright standing [11].

III.A. Bipedal Postural Control

Bipedal postural control is postural control involving two limbs. This is the typical postural control employed by humans while standing using both legs. In this standing position, the center of gravity is around the middle of the sacrum area [12].

III.B. Monopedal Postural Control

Monopedal (or unipedal) postural control is postural control involving a single limb. In contrast to bipedal postural control in humans, monopedal has a slightly different center of gravity.

Looking at these three components—the cross-education phenomenon, muscle fatigue, and postural control—that have been studied over the last century, we have developed a research idea that uses the influence these three have on each other. Our research will generate a quantitative analysis of the cross-educational phenomenon on postural control by observing contralateral muscle fatigue.

Significance

The significance of this study encompasses three concepts: the cross-education phenomenon, muscular fatigue, and postural control. Postural control is essential in performing our daily tasks and physical activities. Muscular fatigue is a factor that impairs postural control [13]. Cross-education is a phenomenon that can be used to influence one side of the body by training the opposite or contralateral side.

By studying these concepts we expect to be able to better define results of postural control on the contralateral side via cross-education by measuring muscle fatigue. Results from quantitative experiments such as this one are fairly unique and could be of importance to the field and future research directions.

Rationale

Research surrounding postural control of the lower limb through cross-education is very limited. Having an understanding if cross-education can influence postural control of the contralateral lower limb can provide innovative ways of rehabilitation, especially those impacted with an immobilized lower limb.

For example, in a study involving rehabilitation of people with multiple sclerosis, the use of contralateral strength training has shown improved muscle strength performance of the untrained ankle dorsiflexor muscles which translated into improvements of walking performance and mobility [14]. Another similar example is in stroke rehabilitation where a moderate level of evidence for contralateral strength training improvements was seen [15]. These studies are providing new evidence on rehabilitation when it comes to strength training through cross-education.

In the same vein, we want to increase our understanding on postural control training through cross-education and be able to provide evidence via objective data. We also hope this study can provide new insight for various applications, such as physical rehabilitation or performance training.

Materials and Methods

Participants

Twenty individuals (17 males, 3 females) were enrolled in the study (Table 1). Participants were healthy young adults, with no lower extremity injuries, 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.

Mean ± SD demographics	
Age (years)	21.5 ± 2.6
Height (cm)	179.8 ± 9.8
Weight (kg)	78.65 ± 10.0

Table 1: Mean ± Standard Deviation of Demographics of 20 participants (17 males, 3 females).

Equipment and Materials

Postural control data was collected with a force plate (OR6-7, AMTI, Advanced Mechanical Technology, Inc., Watertown, MA) that recorded forces and moment data. Data obtained from the force plate was used to compute center of pressure (COP) trajectories in the anterior-posterior and medial-lateral directions during each balance task.

Procedures

Consent Procedures and Paperwork

Participants completed consenting procedures before performing any task. Additionally, self-reported demographic data, including age, height, weight, and gender, were collected from each participant. Furthermore, each participant filled out the Waterloo Footedness Questionnaire

(Elias, Bryden, & Bulman-Fleming, 1998; See Appendix A). This questionnaire was used to determine a participant's dominant foot for recording muscle activity.

Pre-fatigue Balance Task

Participants performed balance tasks barefoot on the force plate to obtain baseline data. Trials consisted of the following single-leg standing with varying conditions below:

1. Dominant leg on stable surface
2. Nondominant leg on stable surface
3. Dominant leg on unstable surface
4. Nondominant leg on unstable surface

Participants were instructed to maintain an upright stance with hands on hips, to hold the non-weight bearing leg relaxed in a 90-degree knee flexion position, and to maintain a forward gaze at a target located approximately two meters in front of them (Figure 1) for about 60 seconds. Failed attempts were considered as 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.

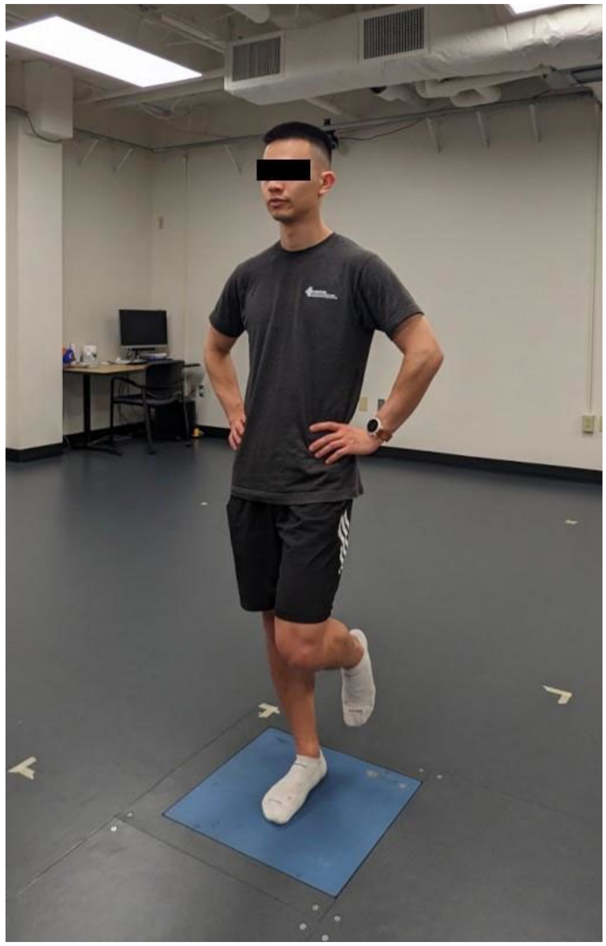

Figure 1. A model demonstrates proper balance stance with unilateral foot on the center of the force plate (the blue-colored metal tile), non-weight bearing leg relaxed in 90-degree position, hands resting on hips, and gaze forward at eye height.

Fatiguing Task (1 of 2)

After the pre-fatigue balance tasks, participants performed a fatiguing task of one-legged calf raises with the dominant leg in the following order:

1. Subjects completed one set of calf raises on the dominant leg to exhaustion (i.e., as many reps as possible until the subject could not do any more) while wearing a shoe on a wood platform that was about 3 to 4 inches high (Figure 2).
2. Rested for 60 seconds while sitting down on a chair.
3. Completed another set of calf raises on the same dominant leg to exhaustion.

Figure 2. A model demonstrates one-legged calf raises on a wood platform.

Post-fatigue Balance Task for Stable Surface

After completing the fatiguing task, participants completed the post-fatigue balance task for stable surface only, which was similar to the pre-fatigue balance task discussed above:

1. Dominant leg on stable surface
2. Nondominant leg on stable surface

Fatiguing Task (2 of 2)

Participants do one more set of calf raises on the dominant leg to exhaustion. This was done since the fatigued leg had already recuperated after the post-fatigue balance task above.

Post-fatigue Balance Task for Unstable Surface

After completing the second fatiguing task, participants completed the post-fatigue balance task for unstable surface this time:

1. Dominant leg on unstable surface
2. Nondominant leg on unstable surface

Results

Data analysis

Data were exported from Qualisys to Matlab (Mathworks, v. 2019b), where custom code was used to compute center of pressure (COP) measurements. COP has typically been used as an index of postural stability during balance tasks and is the point under the sole(s) of the foot (or feet) would be if the pressure of the body was concentrated in one spot [16]. The data from the pre-fatigue balance tasks and post-fatigue balance tasks were analyzed and compared. Graphs and tables were used to illustrate the results.

The independent variables were Phase (pre-fatigue test vs. post-fatigue test) and Surface (stable vs. unstable/foam). 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). Inferential analyses were conducted using analysis of variance (ANOVA) for each dependent variable, followed by a set of comparisons for all Phase pairings.

Coefficient of Variation

The Coefficient of Variation (CV) is a statistical metric indicating the relative variability among a set of data points concerning the mean (average) of the data.[17] It is derived by dividing the standard deviation of the data by the mean. The outcome can be multiplied by 100 to represent it as a percentage.

In other words, the CV offers a standardized gauge of dispersion, enabling the comparison of relative variability among datasets with distinct units or scales. A lower CV implies that data points are in closer proximity to the mean, indicating reduced relative variability, whereas a higher CV suggests heightened relative variability.

For the Coefficient of Variation graphs in the Medial-Lateral direction (CVML), the Pre-fatigue vs Post-fatigue (Fig 3a) has a p-value of 0.076. The CVML for the Stable vs Unstable (Fig 3b) has a p-value of <0.001.

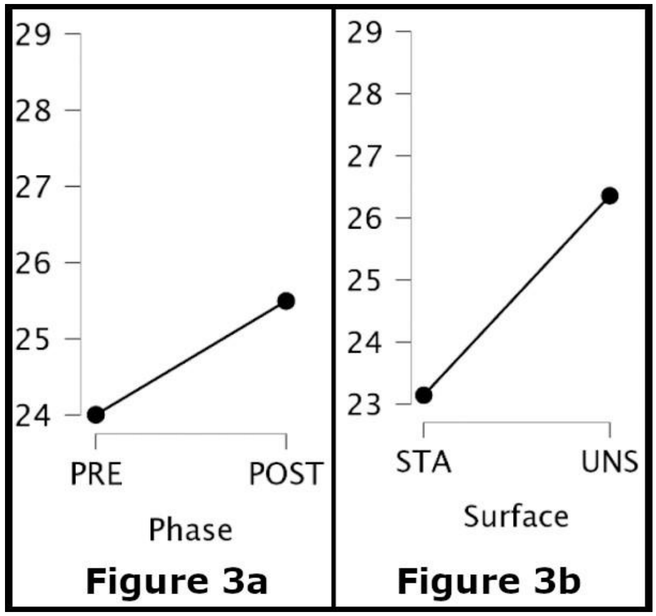

Figure 3. Coefficient of Variation in Medial-Lateral (CVML) direction. (a) Pre-fatigue vs Post-fatigue (Phase) has p-value of 0.076; (b) Stable vs Unstable (Surface) has a p-value of <0.001.

The Coefficient of Variation in the Anterior-Posterior direction (CVAP) also indicates a similar trend in the Pre-fatigue vs Post-fatigue (Fig 4a) and Stable vs Unstable (Fig 4b), with p-values of 0.008 and <0.001, respectively. The graph for the CV trend in the Pre-fatigue vs Post-fatigue specifically for the Dominant Limb and Nondominant Limb (Fig 4c) has a p-value of 0.043.

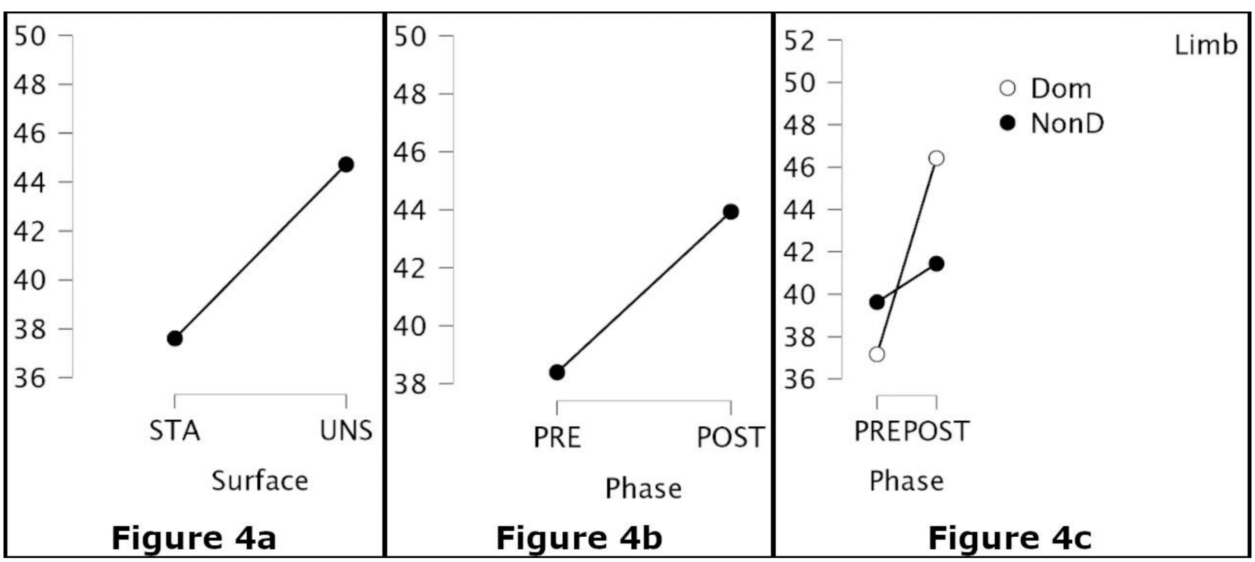

Figure 4. Coefficient of Variation in Anterior-Posterior (CVAP) direction. (a) Pre-fatigue vs Post-fatigue (Phase) has p-value of 0.008; (b) Stable vs Unstable (Surface) has a p-value of <0.001; (c) Pre-fatigue vs Post-fatigue for each Limb has a p-value of 0.043.

Discussion and Innovation

For the Coefficient of Variation graphs in the Medial-Lateral direction (CVML), the increase in the numeric value indicates more sway for Pre-fatigue vs Post-fatigue (Fig 3a) with a p-value of 0.076, and Stable vs Unstable (Fig 3b) with a p-value of <0.001.

Looking at the graph for the CV trend in the Pre-fatigue vs Post-fatigue specifically for the Dominant Limb and Nondominant Limb (Fig 4c) with a p-value of 0.043, the Dominant Limb has a very noticeable steep increase. This indicates that the fatigued gastrocnemius has high CVAP sway, while unfatigued Nondominant Leg has less sway. The sway exhibited in the Dominant leg as indicated by the CV in AP direction is likely due to the fatigue experienced and probably related to the sagittal elements of the heel raise. The moderate amount of increase in the Nondominant limb could be a crossover effect of the fatigue.

This study was designed as a proof-of-principle study. Although the power analysis indicated it was underpowered, the difficulties of obtaining a sufficient sample size (especially without a research grant) precluded the recruitment and enrollment of additional subjects. The research was still valuable in providing preliminary information using this unique set of research approaches to answer our question.

Future Directions

The hypotheses of this study are supported by the data collected; thus, it would suggest that fatiguing the lower limb can influence postural control on the contralateral limb. This is a promising work that can lay the foundation for future research. Cross-education in the context of postural control is not a well-investigated topic and having studies, such as one we have developed, definitely adds more insight on its potential.

Thus, this can become proof of concept that further research is worth pursuing when it comes to contralateral training and its effects on postural control. The more research we have in this topic, the more data we obtain and the better the understanding we would develop. For example, since our research focused on young adults, future research investigating similar effects to the elderly population can definitely add more insight on the effects of contralateral training to postural control.

In addition, the data collected support the hypothesis; thus, it validates the influence of cross-education on postural control and real-world application can be further pursued. For example, the concept could be used as a guide to develop exercise and rehabilitation programs for patients who have muscular or bone injuries in one of their lower limbs where enclosing it in a cast could be necessary thereby rendering it untrained for the duration of the recovery. By having such a program, patients could possibly have faster recovery once their injured limbs have healed. Furthermore, similar rehabilitation programs could also be developed for patients who have neuropathic weaknesses, like those stroke survivors or patients with multiple sclerosis. Of course, application of the exercise/rehabilitation programs to these vulnerable populations would also warrant more research first for these specific populations before such programs are implemented.

Also, since the total number of subjects was small, a few subjects with extremely different performance could have influenced the overall result of the research. Thus, having a small number of subjects can become a confounding factor in itself, and future work with increased power could be a worthwhile pursuit.

Another possible confounding factor is the varying physical abilities of the subjects. Since balancing one's self using a single leg is physical skill, participants who have had less experience in single-leg balancing (e.g., those who may not be as athletic) could possibly have poor performance and influence the overall results in a negative way.

Thus, it is important that possible confounding factors, such as those mentioned above, be noted should they start to impact the results of future research.

Conclusions

In conclusion, this study investigated the acute crossover effects of lower limb muscle fatigue on movement strategies during upright standing in young adults. Utilizing three major concepts—the cross-education phenomenon, muscle fatigue, and postural control—we aimed to understand the influence these factors had on each other. Our study involved 20 participants who underwent pre- and post-fatigue balance tasks on a force plate.

The results revealed a significant increase in the Coefficient of Variation (CV) in both the Medial-Lateral (CVML) and Anterior-Posterior (CVAP) directions for the fatigued Dominant Leg during the post-fatigue balance task, indicating pronounced sway. The unfatigued Nondominant Leg also exhibited increased variability, though to a lesser extent. This effect was attributed to the crossover phenomenon.

Our findings support the hypothesis that acute fatigability in one lower limb influences contralateral postural stability during upright standing. This objective observation was substantiated by measurements obtained from the force plate device. The study, despite being underpowered, provides valuable preliminary information and introduces a unique set of research approaches to address our question.

Looking ahead, future research could enhance the study's power, diversify participant demographics, or explore the effects on other limbs. The insights gained from this research contribute to our understanding of postural control training through cross-education and offer evidence for potential applications in physical rehabilitation and performance training.

Overall, our study serves as a proof-of-principle, laying the groundwork for further exploration into the intricate relationship between cross-education, muscle fatigue, and postural control. The results provide a platform for future investigations, guiding the development of targeted exercise and rehabilitation programs for individuals with lower limb injuries or neuromuscular weaknesses.

Resources

This research study was conducted under the supervision and guidance of my mentor, Dr. Adam C. King, Ph.D., who is a professor at the Department of Kinesiology at Texas Christian University (TCU). Participants performed all tasks at TCU's Motor Behavior Laboratory which houses all the aforementioned equipment. Special thanks also to Kuanting Chen, who was a graduate student in Kinesiology, helped in data gathering of the research.

Compliance Plan

This research study required TCU IRB approval. I also have completed all required CITI Training.

Appendix A

Appendix: Waterloo Footedness Questionnaire—Revised

Instructions: Answer each of the following questions as best you can. If you *always* use one foot to perform the described activity, circle **Ra** or **La** (for **right always** or **left always**). If you **usually** use one foot circle **Ru** or **Lu**, as appropriate. If you use **both** feet **equally often**, circle **Eq**.

Please do not simply circle one answer for all questions, but imagine yourself performing each activity in turn, and then mark the appropriate answer. If necessary, stop and pantomime the activity.

1.	Which foot would you use to kick a stationary ball at a target straight in front of you?	La	Lu	Eq	Ru	Ra
2.	If you had to stand on one foot, which foot would it be?	La	Lu	Eq	Ru	Ra
3.	Which foot would you use to smooth sand at the beach?	La	Lu	Eq	Ru	Ra
4.	If you had to step up onto a chair, which foot would you place on the chair first?	La	Lu	Eq	Ru	Ra
5.	Which foot would you use to stomp on a fast-moving bug?	La	Lu	Eq	Ru	Ra
6.	If you were to balance on one foot on a railway track, which foot would you use?	La	Lu	Eq	Ru	Ra
7.	If you wanted to pick up a marble with your toes, which foot would you use?	La	Lu	Eq	Ru	Ra
8.	If you had to hop on one foot, which foot would you use?	La	Lu	Eq	Ru	Ra
9.	Which foot would you use to help push a shovel into the ground?	La	Lu	Eq	Ru	Ra
10.	During relaxed standing, people initially put most of their weight on one foot, leaving the other leg slightly bent. Which foot do you put most of your weight on first?	La	Lu	Eq	Ru	Ra
11.	Is there any reason (i.e. injury) why you have changed your foot preference for any of the above activities?	**YES**	**NO**	(circle one)		
12.	Have you ever been given special training or encouragement to use a particular foot for certain activities?	**YES**	**NO**	(circle one)		
13.	If you have answered **YES** for either question 11 or 12, please explain:					

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