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Acute Knee Extensor Fatigue Does Not Influence Static Balance Control

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Abstract

Falling is a global phenomenon that differentially impacts individuals 65 years and older. In addition to the physical and financial burdens related to falling, loss of balance control can prevent fall-susceptible people from maintaining an active, healthy lifestyle. Many factors can influence balance control, including muscle fatigue. The purpose of this investigation was to determine if acute fatigue of the knee extensors impacted balance control as assessed by two commercially available balance scales. Sixteen healthy young adults underwent a bilateral knee extensor fatiguing protocol. Peak knee extensor torque (PT) and static balance were assessed before and after fatiguing. Static bipedal balance was measured using the Zibrio Smart Home scale and the NeuroCom Balance Master. Although males displayed greater PT throughout the testing, both sexes displayed the same pattern of PT recovery. Statistical testing revealed that knee extensor fatigue had no negative effects on balance control, based on the testing with either measurement device. There was no relationship between the Zibrio and NeuroCom balance scores prior to fatiguing but negative correlations emerged during the recovery periods. This finding suggests that the two technologies may be measuring different aspects of balance control.

Keywords: Muscle; Fatigue; Exercise; Balance; Falls; Aging

Introduction

Globally, the World Health Organization estimates that there are 684,000 fatal falls each year, with an additional 37.3 million falls requiring medical interventions. In the United States, falls are the leading cause of fatal and non-fatal injury among individuals 65 years and older. It has been estimated that 2.8 million Americans are treated each year for fall-related injuries with approximately 800,000 requiring hospitalizations [1]. The financial burden of falls is approximately $50 billion per year and is expected to increase as current generations continue to age. Moreover, it is important that balance control is maintained in elderly individuals so they can maintain a physically active lifestyle, including regular exercise, thereby preventing the negative consequences of a sedentary lifestyle. Thus, it is clinically and societally important to have accurate methodologies and technologies for predicting which adults have an increased likelihood of falling, such that specific exercise interventions can be designed and used to prevent said falls.

Static balance – defined as the ability to maintain postural stability with minimal sway – is often measured using a force plate [2]. The Zibrio Stability Home scale (Zibrio, Inc., Houston, TX, USA) is a portable force platform that provides an objective assessment of postural stability ranging from 1-10 (Postural Stability score, or PS). The greater the PS, the greater the individual's postural stability. The Zibrio requires only 60 seconds of quiet stance to obtain a valid and reliable balance assessment and can reliably predict an individual's likelihood of falling [3]. Knowing the likelihood of falling provides individuals and clinicians with information that can be used to design intervention programs that improve balance control before a fall takes place.

There are many factors that negatively impact balance, such as fear of falling [4], previous physical injuries, pharmacological agents including alcohol, [5, 6], obesity [7], sleep deprivation [8], and neuromuscular disorders [9]. Lack of muscle strength [10] and fatigue [11, 12] can also negatively impact balance, especially in elderly populations suffering from sarcopenia.

Multiple studies have assessed balance control after inducing acute lower limb muscle fatigue. These studies support the hypothesis that lower limb muscle fatigue results in degraded balance performance [12, 13]. Studies of fatiguing ankle musculature consistently reveal deficits in a variety of balance measures [14-21]. There is a consensus that fatiguing the ankle and hip musculature results in balance deficits, however there are conflicting results regarding whether fatiguing the thigh musculature negatively affects balance control. Kwon [14] reported a significant decrement in unipedal balance after fatiguing the thigh muscles, although this decrease was less than the that associated with ankle musculature fatigue. Bellow et al [22] found that dynamic balance was reduced following both ankle and thigh muscle fatigue, though only ankle fatigue caused static balance deficits. Simultaneous fatiguing of the hamstrings and quadriceps resulted in significant decreases of about 5% in dynamic stability [13]. Using drop jumps to induce fatigue across the lower limb musculature, Hill et al. found increases in center of pressure (COP) displacement in the anterior-posterior and medio-lateral directions during bipedal static balance [12]. Gribble and Hertle reported increases in COP velocity during a unipedal static balance task after inducing thigh musculature fatigue [11]. Marchetti et al (2013) used a leg press exercise to induce fatigue of the lower limb extensors and assessed balance during bipedal stance using measures of COP speed, standard deviation, and ellipse area [23]. Their results revealed no main effect of fatigue on any of the measures, although the authors did report a fatigue effect on COP speed during post-hoc testing. It should be noted that in the above studies, thigh musculature was fatigued simultaneously with other leg musculature, and was assessed with dynamic balance tests or during unipedal balance.

We could only identify a single study that independently fatigued the knee extensors and then assessed bipedal postural control [24]. The results of this study revealed that isolated fatigue of the knee extensors had no impact on balance as assessed by mean COP velocity, ellipse area, and time-to-boundary. However, the possible impact of acute thigh musculature fatigue on static bipedal stance are still unclear. Therefore, the purpose of this study was to investigate the effect of fatigue of the knee extensors on static bipedal balance using the Zibrio Stability Home scale. Additionally, a subset of the participants also had their balance assessed using the NeuroCom Balance Master (NeuroCom, Clackamas, OR, USA) with the results of the Zibrio and NeuroCom being compared.

Methods

Participants

Sixteen healthy, college-aged, individuals participated in the study. Prior to participation, individuals completed a health screening questionnaire and were fully informed both verbally and in writing about the procedures and potential risks associated with participation in the study. All work was performed in accordance with the 1964 Declaration of Helsinki. Each participant signed the subject consent form that had been approved by the University of Houston's Institutional Review Board (ID: 00001746). Of the 16 participants, the results of 12 are reported here as only these individuals met the requirements for inclusion in the data analyses phase of the study (see Statistical Analyses section). By self-report, all were moderately active and none of the participants had any injuries or any neuromuscular conditions that would negatively impact their balance. Potential participants were instructed not to drink alcohol the night before testing. Of the 12 participants whose data is reported, six were female. The mean age of these participants was 20.75 years (SD = 0.62) with no difference between the mean age of the female and male participants. All participants self-reported to be right leg dominant by indicating they kicked a soccer ball with their right foot.

Balance Assessment

Prior to balance testing, the participants warmed up by first performing two sets of 10 unloaded squats (i.e., only their own body weight), followed by five minutes of riding a stationary bike at a comfortable pace [25]. To assess static bipedal balance, the Zibrio Stability Home Scale was used for all 12 participants. The Zibrio scale is a 42.5" x 42.5" x 5.1" force platform that can be used on any flat and firm surface. Participants stood on the Zibrio in their stocking feet, arms at their side, eyes open, and looked at a target placed at eye level two meters in front of them. They were told to remain as still as possible for one minute while data was collected. Prior to data collection, but following their warm-up, the participants received three practice trials on the Zibrio before a single Pretest trial was captured. For those participants being tested on the NeuroCom Balance Manager, three practice trials were given on the stable support surface, with eyes open, prior to a single 20-second Pre-test trial. Equilibrium scores were also calculated by the NeuroCom system software for these participants.

Fatiguing Protocol

Prior to inducing fatigue, concentric maximum voluntary isokinetic contractions (MVIC) were obtained from the right leg during knee extensions. Participants sat in a Biodex dynamometer (Biodex Medical Systems, Shirley, NY, USA), and Velcro™ straps were tightened across the participants' hips and upper body to provide stabilization. The input axis of the dynamometer was then aligned with the lateral femoral condyle of the right knee and active range of motion for each participant was determined with the use of the Biodex software. The participants were provided three practice contractions to ensure they understood the task (i.e., continuous maximal knee extensions and flexion efforts at 60°·s-1). The MVICs were then obtained by having the participants perform three consecutive maximal effort movements. The highest recorded torque (peak torque - PT) of the three contractions was considered the MVIC with corrections for the gravitational effects of segment mass and the dynamometer attachment [10, 26].

After collecting the MVICs, the fatiguing protocol was initiated. A leg extension machine and a combination of free weight plates was used to induce bilateral knee extensor muscular fatigue. The protocol began with a specific warm-up using a relatively low amount of weight and having the participant perform a series of 10 knee extensions. This approach was utilized to ensure that no participant pulled a muscle during the fatiguing protocol.

After the initial set of knee extensions, a forward and backward pyramidal design was used to induce fatigue [27]. Participants were told to contract their muscles to extend their knee through normal range of motion as rapidly as possible, while not resisting during the return phase (flexion) of the weight. Participants were also instructed to grasp the handle of the leg extension device, which provided them with additional leverage to maintain maximal contractions.

Initial weight was determined based on personalized assessments of each participants' estimated strength. The forward phase of the pyramidal design consisted of the participants performing five extension repetitions before weight was increased. Movements were then repeated five times, and weight was again increased. This process was repeated until the participant could no longer move the leg through the entire range of motion. The backward phase of the pyramid was then initiated, with the weight being reduced and the movements repeated. This process continued until the weight reached the amount that was used during the initial knee extension and the participant was no longer able to perform a single extension. To ensure fatigue, once they could no longer perform a single contraction, they were provided 10 seconds of rest and then were asked to perform additional extensions until they were again no longer to achieve a single knee extension. While there was no predetermined set time to conduct the fatiguing protocol, all subjects reached 'fatigue' within five to seven minutes of beginning the protocol. During the contractions, participants were provided loud verbal encouragement designed to assist them in providing their maximal effort during the protocol.

After the fatiguing protocol was completed, participants returned to the Biodex and three maximal contractions were performed. Participants' balance was then immediately tested on the Zibrio before moving to the Balance Master, for those tested with the NeuroCom device. As the Zibrio, NeuroCom Balance and Biodex, and the knee extension machine were within a few feet of each other, it took approximately 15 seconds to move between the completion of each activity and the beginning of the next with the exception of the first torque assessment after the fatiguing protocol (see below) [11]. In addition to the Pretesting, data were collected immediately after fatiguing, and then again after 5, 10, 15 minutes after completion of each collection session. After completing the strength and the two posture tests during the recovery periods, the participants sat quietly until it was time to again begin the assessments. These post-fatigue data collections sessions were labeled Recovery 1, 2, 3, and 4, respectively. Table 1 reflects the time course of the collection protocol.

Table 1: Experimental Protocol

Pretest	FatigueProtocol	Recovery 1(Immediately after Fatiguing)	Recovery 2(5 mins after Recovery1)	Recovery 3(5 mins after Recovery 2)	Recovery 4(5 mins after Recovery 2)
Warm -up					
Zibrio		Biodex	Biodex	Biodex	Biodex
NeuroCom		Zibrio	Zibrio	Zibrio	Zibrio
Biodex		NeuroCom	NeuroCom	NeuroCom	NeuroCom

After testing was completed, the initial step in the analysis was to determine the effectiveness of the fatiguing protocol. A threshold of a 30% decrement in peak knee extension torque relative to maximum pre-fatigue value was set for the participants' data to be included in the subsequent analyses. Of the 16 initial participants, 12 met the criteria for inclusion for additional analyses. These 12 included six males and six females. Due to technical issues with the NeuroCom Balance Master, ES scores were only able to be obtained from 10 of the 12 participants.

Prior to implementing statistical analyses, the data were checked for normality and homogeneity of variance using the Kolmogorov-Smirnov and Leven's tests, respectively. Potential differences in the generation of PT between males and females were initially evaluated by developing grand means and standard deviations of PT for each sex. The values were then collapsed over the testing periods and a t-test was used to determine if there were differences between the two sexes. To explore the recovery in response to the fatiguing protocol, fatigue indices (FI) for each participant using the following formula (Recovery Increment PT – Pre-fatigue PT/Pre-fatigue PT x 100) for each recovery period were calculated [28]. A 2 x 2 ANOVA was used to assess whether the FI values reflected similar recovery profiles for females and male with post-hoc t-test using corrected p values, exploring possible sex differences during each recovery period. After determining that males and females responded to the fatigue protocol with the same pattern of percentage decrements in each recovery period, the dependent variables were collapsed over sex. Grand means and standard deviations were then obtained for each variable and each period.

One-way, repeated measures analysis of variance (ANOVA) for each dependent variable, were then conducted. If main effects were identified, post-hoc testing with corrected p values was used to identify which comparisons were significantly different. To determine if there were relationships between any of the dependent measures, Pearson R correlations were also computed. Finally, we correlated the FI scores in the Recovery 1 period with the PS scores and then with the ES scores to determine if there were relationships between the amount of PT decrement relative to the pre-fatigue PT and the two balance measures.

Results

Peak Knee Extensor Torque (PT)

As anticipated, there was a significant effect for gender $t(29) = -7.53$, $p < 0.0001$, with males overall mean PT being 151.1 (SD = 33.2) and females generating 84.9 (SD = 34.9) N*m. However, as the recovery profiles were the same for both males and females, the dependent measures were then collapsed over sex. Figure 1 displays group means, and standard deviations for PT for each testing period. The results on the ANOVA testing indicated there was a main effect of period ($F(4,55) = 31.36$, $p < 0.00001$). Post-hoc testing revealed a significant difference between the mean pretest (151.1, SD = 49.0) and the first recovery period (91.4, SD = 37.3) N*m, ($t = 7.88$, $p < 0.00001$). No other comparisons reached significance.

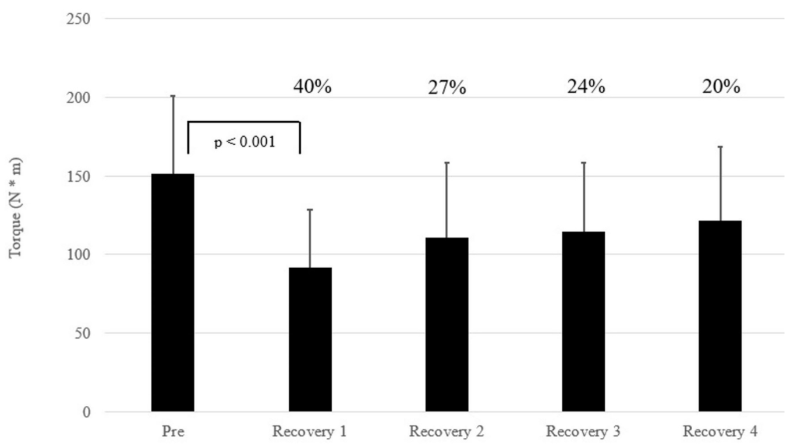

Figure 1: Means (+SDs) of peak torque during the Pre-fatigue and Recovery periods. The percentage values represent the percentage decrease of that score relative to the Pre-fatigue value.

The results of the 2 x 2 ANOVA did not reveal significant main effects or interactions of sex, but there was significant effect of period ($F(3,40) = 4.10$, $p < 0.013$). Post-hoc testing between males and females revealed no significant differences at any of the recovery periods indicating the pattern of fatigue recovery was the same for the two sexes. Figure 2 displays the FI values during the recovery periods relative to Pre-fatigue PT values with Pre-fatigue reflected as 100. It can be observed that despite 20 minutes of recovery, PT remains at only 80% of Pre-fatigue PT values.

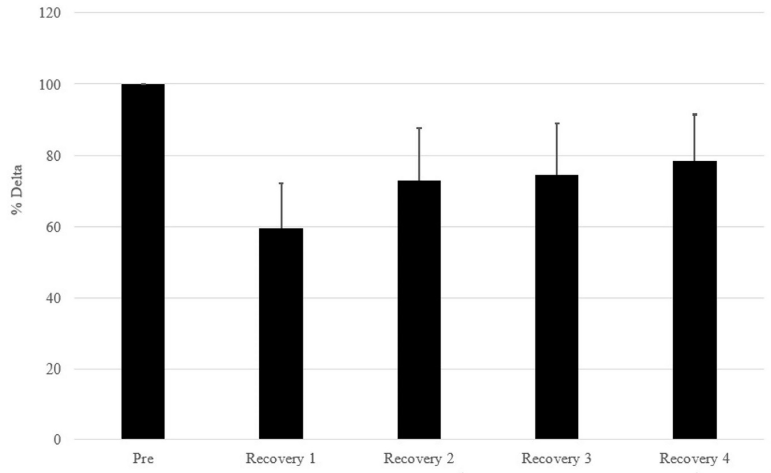

Figure 2: Means (+SDs) of % difference between Pre-fatigue PT and Recovery periods. Pretest PT is represented as 100.

Zibrio Stability Home Scale Postural Stability Scores (PS)

The mean and standard deviations of the Zibrio Postural Stability scores are presented in Figure 3. ANOVA testing indicated there were no main effects between the testing periods F(4,55) = 1.59, p <0.1940.

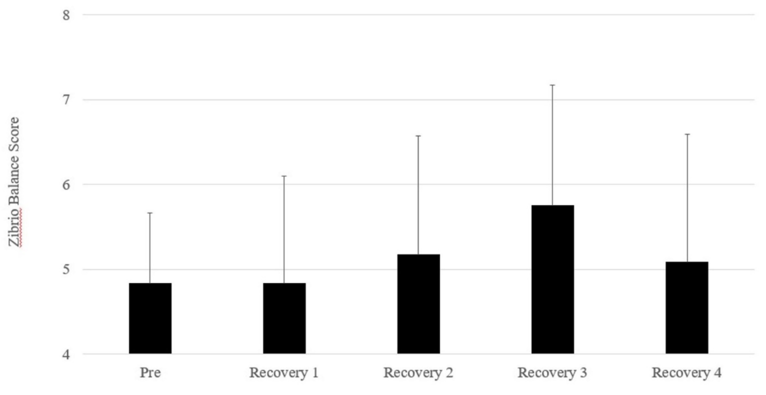

Figure 3: Means (+SDs) of Zibrio postural stability scores during the Pre-fatigue and Recovery periods.

NeuroCom Balance Master Equilibrium Scores (ES)

Similar to the results of the Zibrio balance testing, there was no main effect reflected in the ESs (F(4,45) = 2.30, p < = 0.0772, Figure 4).

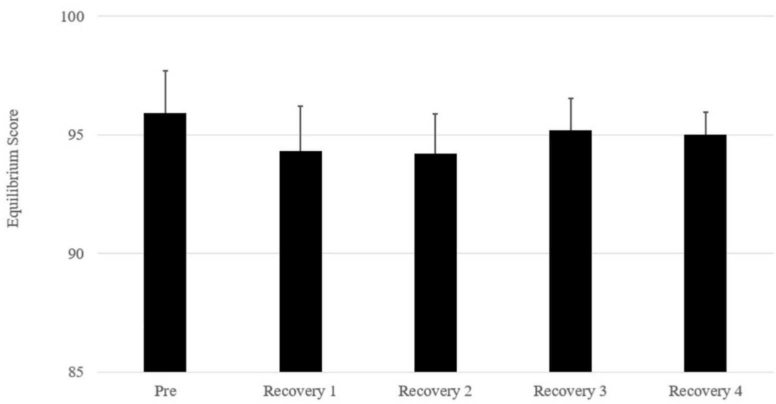

Figure 4: Means (+SDs) of Balance Master equilibrium Scores during the Pre-fatigue and Recovery periods.

The results of both balance tests reveal that knee extensor fatigue did not result in decreases of static balance performance in the tested balance measures.

Correlations

Table 2 displays the Pearson r values between the dependent variables.

Table 2: Correlation values between balance scores and peak torque

Pearson r Correlations	Pre	Recovery 1	Recovery 2	Recovery 3	Recovery 4
PS vs PT	0.55	0.35	-0.08	0.36	0.23
PS vs ES	-0.01	-0.43	-0.38	-0.36	0.30
ES vs PT	-0.27	0.29	0.07	-0.13	-0.38

It can be observed that there is a moderate positive relationship between PS scores and PT prior to fatigue [29]. During Recovery period 1 and 3, there is a weak relationship between these two measures. In the Pre period, there is no association between the PS and ES, while during the recovery periods there are weak relationships between the two variables. Interestingly, Recovery periods, 1, 2, and 3 all display negative coefficients. Recovery 4 displays a weak positive relationship. When comparing the ES and PT, there is a weak negative coefficient in the Pre period with weak to no relationship during the recovery periods. While weak, there is a negative relationship in the last recovery period. The relationship between the FIs in the recovery period and the PS and ES were -0.15 and 0.38, respectively.

Discussion

The loss of balance and subsequent falls are a significant deterrent to indiviuals who may otherwise want to be involved in a regular exercise regime. Understanding the impact of muscle fatigue on balance control provides insights to clinicians and exercise therapists that enable them to provide effective exercise prescriptions. Moreover, understanding what information is being provided by a particular balance assessment score, can guide the development of a exercise plan designed to ameliorate specific weaknesses in an individual's balance profile.

As anticipated, there were significant differences in PT knee extensor values between the males and females [14, 30]. Despite absolute differences in PT between males and females, the percentage reductions from pre-fatigue PTs and post-fatigue protocol and the pattern of torque recovery were the same between the two sexes. Based on the definition of fatigue being 'a loss of maximal force generating capacity' [31-33], our subjects' 40% loss of peak torque during the initial recovery balance testing indicated significant fatigue of the knee extensor muscles. Palliard [34] reported that most studies of balance control and leg muscle fatigue are likely to induce balance decrements if loss of MVC PT is 30% or more [34].The decrement observed in the current study is similar to the 44% decrease in knee extensor peak torque found during post-fatigue testing in Arora, et al. [35]. Moreover, the fact that even at the conclusion of 20 minutes of recovery, peak torque remained 20% below their peak torque reflects the effectiveness of the fatiguing protocol.

The data clearly indicate that significant fatigue of the thigh extensor muscles did not negatively impact static balance control with eyes open when assessed by the Zibrio Stability Home scale and the Neurocom Balance Master. Although there is general consensus that fatiguing knee extensors has negative effects on unipedal static balance [14, 36], but see [22], the literature is mixed whether such fatigue also decreases bipedal balance. Several investigations indicated that fatiguing the knee extensors impaired balance though these studies did not examine the knee extensors in isolation [11, 12, 37, 38]. Conversely, Lin, et al. and Arora, et al., found no effect of isolated knee extensor fatigue on bipedal balance [24, 34]. Moreover, Winter, et al., unequivocally states that there is no role for knee extensors in static bipedal stance when the authors stated that during bipedal stance "A/P balance is totally under ankle (plantar/dorsiflexor) control" (p. 2334) [39].

The current data supports the contention that knee extensor fatigue does not result in decreases in static bipedal balance. This is consistent with the studies referenced above and supported by several studies that also assessed electromyographic (EMG) data during bipedal standing tasks. Laughton, et al, [40] reported negligible EMG activity of the vastus lateralis during quiet stance. In fact, young participants displayed muscle activity that was below resting baseline levels obtained during supine positioning [40]. Moreover, the vastus lateralis was reported 'active' during only 5% of 300 secs of quiet stance (10 trials of 30 secs). Consistent with the findings of Laughton, et al., a recent study by Clarke, Al-Hammdany and Di Giulio initially placed participants in supine position on a motorized plinth and the orientation angle was incrementally increased the until the participants were upright (90 degrees) [41]. The participants were instructed to relax as much as possible. The EMG of the lower limb musculature was obtained and compared at each of eight different orientations and relative to unsupported upright stance without the plinth. During unsupported stance, neither the rectus femoris nor vastus medialis displayed any measurable activity, while the vastus lateralis displayed a slight increase in neuromuscular activity relative to the supine position.

The two EMG studies above support Winter, et al.'s contention that the knee extensors have no role in bipedal quiet stance [39]. Given the evidence that the knee extensor musculature has little to no role in static bipedal balance, it is not surprising that the current investigation found that knee extensor fatigue did not result in decrements of balance scores. As unperturbed bipedal stance is controlled by the ankle musculature fatigue of the knee extensors would not be expected to significantly influence static balance performance [27, 36, 39].

Examining the correlations between the dependent measures, it can be observed there is a moderate relationship between the PS and PT scores in the pre-fatigue period which decreases to a weak relationship when these scores are compared in Recovery 1 period (Table 2). These relationships are consistent with previous research which has indicated there is a moderate relationship between knee extensor strength and balance [10, 42]. In contrast, the relationships there was a weak negative correlation between the PT and ES scores in the pre-fatigue period but a weak positive relationship in the Recovery 1 period. The number of weak to low correlations between the dependent variables indicates there is little relationship between the current measures of PT and the balance scores from either assessment technology. This is consistent with Granacher & Gollhofer's report of only minor associations between lower limb strength and static balance control [43].

During the Pre-fatigue period, the -0.01 correlation between the BS and ES scores indicate there is no relationship between the balance performance on the two assessment technologies (Table 2). The low but negative relationships in Recovery period 1, 2, and 3 and the low but positive relationship in the Recovery 4 period, suggest that the Zibrio Stability Home scale and the NeuroCom Balance Master may be utilizing different aspects of bipedal sway in the computation of their outcome scores.

There are several limitations in the current study that limit the generalizability of the results and the associated conclusion that isolated knee extensor fatigue is not associated with decrements in balance performance. The first is the relatively small sample size. It is possible that an examination using a larger sample would be more sensitive to the effects of knee extensor fatigue on balance. In addition to the small sample size, testing of indidviduals from populations other than young, healthy individuals, for example, elderly individuals may lead to different results. It has been reported that older adults produce less torque using the ankle plantar flexors [44]. As mentioned above, these muscles are primarily responsible for balance control during quiet bipedal stance. The reduction in torque production of the plantar flexors in older adults could result in activation of the knee extensors to compensate for the reduction. If so, fatiguing of the knee extensors in older adults may result in decreases in balance.

A second limitation relative is that both current measurement technologies provided a single value to represent balance. This contrasts with other studies that investigated the association between lower limb muscle fatigue and static balance. The vast majority of these studies used several measures obtained from force-plate derived forces and center of pressure sway measures to evaluate balance control. Thus, direct comparisons between most previous studies and the results obtained from the Zibrio and NeuroCom are difficult. However, it should be kept in mind that the above two technologies were developed for different purposes than laboratory-based balance assessment technologies, even though they also use force plate-based measures of balance.

The Zibrio Stability Home scale and NeuroCom Balance Master are both designed to provide easily understandable information that can utilized by clinicians, patients, and healthy individuals to make informed choices about interventions or their own future behavior, respectively. The loss of balance and subsequent falls are a significant deterrent to individuals who may otherwise want to be involved in a regular exercise regime. Understanding the impact of muscle fatigue on balance control provides insights to clinicians and exercise therapists that enable them to provide effective exercise prescriptions. Moreover, understanding what performance factors are contributing to a particular balance assessment score can guide the development of an exercise plan designed to ameliorate specific weaknesses in an individual's balance profile.

Conclusions and Future Directions

The current results indicate that knee extensor fatigue does not decrease balance during static bipedal stance using two commercially available balance scales. Moreover, the lack of relationships between the balance scores obtained on the two suggests that the Zibrio Stability Home scale and the NeuroCom Balance Master may be evaluating different aspects of static balance control when computing their balance scores. Both technologies produce balance scores that are associated with the likelihood of future falls, although the Smart Home scale reports a score that is directly associated with this likelihood following a single, eyes-open bipedal stance test. Having the knowledge about the likelihood of a fall provides individuals susceptible to falls the ability to undertake physical activities aimed at preventing possible falls. Finally, while the current study adds to the literature concerning the possible relationship between knee extensor fatigue and static balance, the question remains unresolved. This is likely because investigations of lower limb fatigue and balance have employed a variety of muscle fatiguing as well as balance assessment protocols. Standardizing both protocols would help answer questions related to the potential associations between lower limb fatigue and balance control and under what conditions such association may exist. Such information would be valuable both to clinicians and individuals interested in predicting and preventing falls. Future directions include replicating this study with a sample of elderly participants. Additionally, exploring the effect of isolated muscle fatigue versus systemic muscle fatigue following lower limb exercise activities, such as cycling or running, will provide additional insight into the role of muscle fatigue on balance control.

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References

1. GD Bergen, MS Stevens, ER Burns (2016) "Falls and fall injuries among adults aged ≥65 years – United States, 2014," *Morbidity and Mortality Weekly Report*, 65: 993-8.

2. L Ricotti (2011) "Static and dynamic balance in young athletes," *Journal of Human Sport and Exercise*, 6: 616–28.

3. KE Forth, KL Wirfel, SDAdams et al. (2020) "A postural assessment utilizing machine learning prospectively identifies older adults at a high risk of falling," *Frontiers in Medicine*, 7: 591517.

4. WR Young, AM Williams (2015) "How fear of falling can increase fall-risk in older adults: applying psychological theory to practical observations," *Gait & Posture*, 41: 7-12.

5. MH de Groot, JP van Campen, MA Moek et al. (2010) "The effects of fall-risk-increasing drugs on postural control: a literature review," *Drug & Aging*, 30: 901-20.

6. A. Holton F Boland, P Gallagher et al. (2019) "Potentially serious alcohol-medication interactions and falls in community-dwelling older adults: a prospective cohort study," *Age and Ageing*, 48: 824-31.

7. L Zhang, S Liu, W Wang et al. (2022) "Dynapenic abdominal obesity and the effect on long-term gait speed and falls in older adults," *Clinical Nutrition*, 41: 91-6.

8. NA Knechel, PS Chang (2022) "The relationships between sleep disturbance and falls: A systematic review," *Journal of Sleep Research*, 31: e13580.

9. S. Kröger and B. Watkins (2021) "Muscle spindle function in healthy and diseased muscle," *Skeletal Muscle*, 11: 1.

10. MJ Karabin, PJ Sparto, C Rosano et al. (2022) "Impact of strength and balance on Functional Gait Assessment performance in older adults," *Gait & Posture*, 91: 306-11.

11. PA Gribble and J Hertel (2004) "Effect of lower extremity muscle fatigue on postural control," *Archives of Physical Medicine and Rehabilitation*, 85: 589-92.

12. M Hill K, Rosicka, M Wdowski (2021) "Effect of sex and fatigue on quiet standing and dynamic balance and lower extremity muscle stiffness," European *Journal of Applied Physiology*, 122: 233-44.

13. PB Costa, CV Ruas, CM Smith (2018) "Effects of stretching and fatigue on peak torque, muscle imbalance, and stability," *Journal of Sports Medicine and Physical Fitness*, 58: 957-65.

14. OY Kwon, HS Choi, CH Yi, et al. (1998) "The Effects of Knee and Ankle Muscles Surrounding the Knee and Ankle Joints on One-Leg Static Standing Balance," *Journal of Physical Therapy Science*, 10: 7-12.

15. KM Harkins, CG Mattacola, TL Uhl et al. (2005) "Effects of 2 ankle fatigue models on the duration of postural stability dysfunction," *Journal of Athletic Training*, 10: 191-4.

16. P Hlavackova, D Pradon, N Vuillerme (2012) "Control of bipedal posture following localised muscle fatigue of the plantar-flexors and finger-flexors," *European Journal of Applied Physiology*, 122: 789-93.

17. D Jo, M Pannetier, S Drouin et al. (2022) "Sex differences in the effect of muscle fatigue on static postural control under different vision and task conditions," PLoS One, 17: e0269705.

18. TM Lundin, JW Feuerback, MD Grabiner (1993) "Effect of plantar plantar flexor and dorsiflexor fatigue on unilateral postural control," *Journal of Applied Biomechanics*, 9: 191-201.

19. DT Ochsendorf, CG Mattacola, BL Arnold (2000) "Effect of orthotics on postural sway after fatigue of the plantar flexors and dorsiflexors," *Journal of Athletic Training*, 35: 26-30.

20. A Remaud, C Thuong-Cong, M Bilodeau (2016)"Age-Related Changes in Dynamic Postural Control and Attentional Demands are Minimally Affected by Local Muscle Fatigue," *Frontiers in Aging Neuroscience*, 21. doi: 10.3389/fnagi.2015.00257.

21. N Vuillerme, V Nougier, J Prieur (2001) "Can vision compensate for a lower limbs muscular fatigue for controlling posture in humans?," *Neuroscience Letters*, 308: 103-6.

22. JW Bellew, PC Fenter (2006) "Control of balance differs after knee or ankle fatigue in older womem," *Archives of Physical Medicine and Rehabilitation*. 87: 1486–9.

23. PH Marchetti, MI Orselli, M Duarte (2013) "The effects of uni- and bilateral fatigue on postural and power tasks," *Journal of Applied Biomechanics*, 29: 44-8.

24. D Lin, MA Nussbaum H Seol et al. (2009) "Acute effects of localized muscle fatigue on postural control and patterns of recovery during upright stance: influence of fatigue location and age,". *European Journal of Applied Physiology*, 106: 3: 425-34.

25. AC Parcell, RD Sawyer, VA Tricoli et al. (2022) "Minimum rest period for strength recovery during a common isokinetic testing protocol," *Medicine* & *Science in Sports* & *Exercise*, 34: 1018-22.

26. EC Conchola, BJ Thompson, DB Smith (2013) "Effects of neuromuscular fatigue on the electromechanical delay of the leg extensors and flexors in young and old men," *European Journal of Applied Physiology*, 113: 2391-9.

27. P Corbeil, JS Blouin, F Bégin et al. (2003) "Perturbation of the postural control system induced by muscular fatigue," *Gait* & *Posture*, 18: 92-100.

28. S Sangnier C Tourny-Chollet (2008) "Study of the fatigue curve in quadriceps and hamstrings of soccer players during isokinetic endurance testing," *Journal of Strength and Conditioning Research*, 22: 1458-67.

29. J Cohen (1998) Statistical Power for the Behavioral Sciences. Hillsdale, NJ: Erlbaum.

30. LA Wojcik, MA Nussbaum, D Lin et al. (2011) "Age and gender moderate the effects of localized muscle fatigue on lower extremity joint torques used during quiet stance," *Human Movement Science*, 30: 574-83.

31. B Bigland-Ritchie, E Cafarelli, NK Vøllestad (1986a) "Fatigue of submaximal static contractions," *Acta Physiologica Scandinavica*, 128: 137-48.

32. NK lestad, OM Sejersted, R Bahr et al. (1988) "Motor drive and metabolic responses during repeated submaximal contractions in man," *Journal of Applied Physiology*, 64: 1421–7.

33. NK lestad (1997) "Measurement of human muscle fatigue," *Journal of Neuroscience Methods*, 74: 219-27.

34. T Paillard (2012) "Effects of general and local fatigue on postural control: a review," *Neuroscience and Biobehavioral Reviews*, 36: 162-76.

35. Arora S, Budden S, Byrne JM, Behm DG (2015) "Effect of unilateral knee extensor fatigue on force and balance of the con-

tralateral limb," *European Journal of Applied Physiology*, 115: 2177-87.

36. EJ Bisson, D McEwen, Y Lajoie et al. (2011) "Effects of ankle and hip muscle fatigue on postural sway and attentional demands during unipedal stance," *Gait* & *Posture*, 33: 83-7.

37. PK Miller, AM Bird AM (1976) 'Localized muscle fatigue and dynamic balance," *Perceptual and Motor Skills*, 42: 135-8.

38. V Chaubet, T Paillard (2012) "Effects of unilateral knee extensor muscle fatigue induced by stimulated and untary contractions on postural control during bipedal stance," *Neurophysiologie Clinique*, 42: 377-83.

39. DA Winter, F Prince, JS Frank et al. (1996) "Unified theory regarding A/P and M/L balance in quiet stance," *Journal of Neurophysiology*, 75: 2334 – 43.

40. CA Laughton, M Slavin, K Katdare et al. (2003) "Aging, muscle activity, and balance control: physiologic changes associated with balance impairment" *Gait* & *Posture*, 18: 101-8.

41. B Clarke B, JK Al-Hammdany, I Di Giulio (2023) "Human muscle and spinal activation in response to body weight loading," *Journal of Anatomy*, 242: 745-53.

42. SG Kim, WS Kim (2018) "Effect of Ankle Range of Motion (ROM) and Lower-Extremity Muscle Strength on Static Balance Control Ability in Young Adults: A Regression Analysis," *Medical Science Monitor*, 15: 3168-75.

43. U Granacher, A Gollhofer (2011) "Is there an association between variables of postural control and strength in adolescents?" *Journal of Strength and Conditioning Research*, 25: 1718-25.

44. LA Barber, RS Barrett RS, JG Gillett et al (2013) Neuromechanical properties of the triceps surae in young and older adults. *Experimental Gerontology*, 48: 1147-55.