8-2024

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Recommended Citation

Worley, Brayden, "Acute Effects of Multi-Joint Eccentric Exercise on Lower Extremity Muscle Activation Measured During Land and Water Walking" (2024). *All Graduate Reports and Creative Projects, Fall 2023 to Present*. 41.
https://digitalcommons.usu.edu/gradreports2023/41

ACUTE EFFECTS OF MULTI-JOINT ECCENTRIC EXERCISE ON LOWER EXTREMITY MUSCLE ACTIVATION MEASURED DURING LAND AND WATER WALKING

by

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A plan B research project submitted in partial fulfillment
of the requirements for the degree

of

MASTERS OF SCIENCE

in

Kinesiology

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2024

Abstract

Although prior literature has established the preliminary clinical benefits of aquatic exercise across various clinical populations, there is a need to explore the potential for including aquatic-based movement as a key component of a multi-modal approach toward improving mobility and reducing fall risk. Eccentric exercise may complement aquatic exercise given that movements performed in water immersion tend to be low impact. Eccentric exercise may also improve the passive stiffness of lower extremity extensors, which gives an additional rationale for the potential of eccentric exercise to reduce fall risk when combined with aquatic exercise. There may also be an acute response to spinal reflex activity post-eccentric exercise, which could enhance the benefit of performing aquatic exercise if eccentric exercise is performed immediately prior. The purpose of this study was to compare lower-limb muscle activation during gait performed in water versus on land, before and after a short bout of eccentric exercise, in order to investigate the potential of a multi-modal approach toward improving gait abnormalities that relate to fall risk in older adults. Twenty-six healthy, recreationally active young adults completed the study. Each participant walked on land and in water, both prior to and after eccentric exercise for 2-min each while root-mean-square (RMS) muscle activity of the tibialis anterior (TA), medial gastrocnemius (GM), biceps femoris (BF), and vastus lateralis (VL) were recorded during the swing and stance phases of gait, using surface electromyography. A two-way within-subjects analysis of variance was used to evaluate for main effects and interactions. Main effects of environment were observed across all measures of muscle activation ($F = 4.5 – 602.6$, $p < 0.001 – 0.036$) except for BF RMS during the swing phase ($F = 0.2$, $p = 0.699$). Co-activation of the thigh during swing was the only measure to reveal an environment × eccentric exercise interaction ($F = 5.4$, $p < 0.001$) and main effect of eccentric exercise ($F = 7.4$,

$p = 0.008$).The significant interaction on Co-activation of the thigh during swing appeared to be influenced by a non-significant reduction in VL RMS observed for post-eccentric exercise land walking. This suggests that participants may have adopted a different motor strategy, possibly anticipating the greater vertical ground reaction forces during foot impact in land walking compared to water walking, leading to reduced VL activation during swing. The results of this study provide evidence that additional research is warranted and may be aimed at exploring the potential of a multi-modal training approach involving aquatic treadmill walking and eccentric exercise to enhance mobility and address fall risk in clinical populations.

Introduction

Research related to aquatic-based exercise and rehabilitation has made significant advancements over the years, establishing a presence within the field (Becker, 2020). One specific area that remains relatively unexplored is the investigation of muscle activity through surface electromyography (sEMG) between land and water environments. There are a few studies that have examined lower extremity muscle activation during walking and running gait performed using a treadmill between land and aquatic environments, with inconsistent results reported (Silvers et al 2014, Heywood et al. 2016, Macdermid et al. 2017, Mitsudo et al. 2008, Rutledge et al. 2007, Shono et al. 2007, So et al. 2022). It is plausible to suggest that at least some of the inconsistencies in results could be influenced by the reliability of collecting sEMG underwater, although Silvers and Dolny (2011) observed no significant differences in maximum voluntary contraction (MVC) during manual muscle testing performed on land and in water, providing evidence that the integrity of sEMG recordings were maintained during water immersion.

In a follow up investigation, Silvers et al. (2014) observed that running in an aquatic environment compared to a land environment yielded mixed effects on lower-extremity muscle activation magnitudes. Specifically, when comparing aquatic running with matched speeds on land, activation magnitudes across the full stride decreased for the vastus medialis (VM) and gastrocnemius (GA) and increased for the rectus femoris (RF) during swing, with no differences observed across the stride cycle for the tibialis anterior (TA) and biceps femoris (BF). The results of this study suggest that muscle activation differences between aquatic and land treadmill running are likely due to effects of environmental variation, such as changes in the hydrodynamic properties of buoyancy and drag.

A crucial aspect of methodological design in aquatic research involves the depth of water (Silvers et al. 2014, So et al., 2022). Silvers et al. (2014) immersed participants to the level of the xiphoid process, which is recommended from prior literature. For example, Macdermid et al. (2017) observed a reduction in stride cadence with concomitant increases in stance and swing time for running performed at increasing levels of water immersion. Further, in a recent study by So et al. (2022), the authors observed a significant increase in stance to swing time ratio with rising water depths (mid-shin to waist level) in addition to effects of water depth on the muscle activation of certain muscles. Specifically, So et al. (2022) observed increased RF activation during the swing phase, which is in agreement with the findings from Silvers et al. (2014). Interestingly, So et al. (2022) also observed increased TA activation during swing and a decrease in BF activation during swing at certain water depths, which is different from the findings by Silvers et al. (2014). It is plausible that the results were influenced by different immersion levels selected across studies signifying the need for further research in the area.

Prior research on aquatic running may not be extrapolated to walking, given that there are notable differences in gait mechanics. For instance, increased lower-extremity flexion during the swing phase likely reduces the projected frontal area of the lower limbs during running, which may also be offset by an increase in limb velocity when compared with walking. A systematic review from Heywood et al. (2016) revealed that self-selected walking speed is lower in water environments though lower limb range of motion and muscle activity were similar. Heywood et al. (2016) suggested drag forces may contribute to the lower self-selected walking speeds and that monitoring the speed of movement in water can help determine the advantages or potential disadvantages of aquatic walking. It is arguable that aquatic-based walking is more relevant to exercise and rehabilitation of clinical populations when compared with running, especially in populations associated with a known increased risk for falling. According to a study conducted by Mitsudo et al. (2008), walking in water may elicit differences in muscle activation, and result in higher cardiorespiratory responses and increased perceived exertion levels in older adults when compared with walking on dry land at the same speed. Further, a separate study was conducted by Shono et al. (2007), with the findings of this study indicating that the muscle activity levels of the TA, VM, and BF were increased significantly in comparison with land walking. However, GA and RF activation magnitudes did not differ significantly, which was attributed to buoyancy, lower cadence, and a moving floor (Shono et al., 2007).

More recently, a study by Long (2023), aimed to compare lower-limb muscle activation during walking gait performed in water and on land, with the goal of finding preliminary evidence that aquatic treadmill walking may be explored further as a treatment for foot drop. The results of this study indicated that TA activity during the swing phase of gait was greater in water than on land, but the GA activity was lower during the stance phase of gait (Long, 2023). Foot drop is a neurological condition that prevents dorsiflexion of the foot while walking. The TA muscle is the primary dorsiflexor, while the GA is the primary plantar flexor, with the activation of both muscles contributing to foot clearance during gait. Given the relevance of ankle mechanics with foot clearance, it may be extrapolated that further research into aquatic-based walking, aimed at increasing the relative activation of the TA with respect to the GM, could fill an important gap in research relating to falling risk.

It is important to carefully design aquatic walking studies that have potential clinical applications. Specifically, in the area of fall risk prevention in older adults, it would be beneficial to submerge participants at the xiphoid level as this level of immersion lowers weight bearing loads by 60% (Choi et al., 2022). Also, submerging to the xiphoid process is considered the maximum depth that maintains a “normal” gait with limited float time (Rutledge et al., 2007). Additionally, aquatic exercise and rehabilitation promotes a safe environment for clinical populations, as evident from self-reported perception provided by older adults in our prior work (Bressel et al., 2017). Further, in addition to providing a safe environment that may facilitate movements that would otherwise be contraindicated on land, aquatic-based movement has also been suggested to have potential efficacy for eliciting concurrent cognitive benefits (Kang et al., 2020).

Although prior literature has established the preliminary clinical benefits of aquatic exercise across various clinical populations, there is a need to explore the potential for including aquatic-based movement as a key component of a multi-modal approach toward improving mobility and reducing fall risk. Eccentric exercise may complement aquatic exercise given that movements performed in water immersion tend to be low load and impact. Eccentric exercise involves the slow, lengthening of a skeletal muscle while under active tension, providing high overload to the muscle. The Eccentron (BTE Technologies Inc., Hanover, MD, USA) is one example of a multi-joint eccentric training device that provides an effective method for conducting eccentric overload exercise that specifically targets lower extremity extensor muscles. It is uncertain as to the extent that eccentric exercise causes acute fatigue in agonist muscle groups, however, acute fatigue may facilitate a greater relative activation of lower extremity flexors versus extensors if walking is performed immediately following a bout of eccentric exercise (Hoppeler, 2016). Eccentric training has been shown to increase activation and strength of lower extremity flexors (Al-Uzri & O’Neill, 2014). For example, eccentric training is observed to increase plantar flexor power, with significant increases observed in individuals who were weaker at baseline (Al-Uzri & O’Neill, 2014). Thus, a combination of aquatic and eccentric exercise may afford a complimentary and efficient multi-modal training approach targeting both improving walking mechanics and lower-extremity power. Considered together, the potential benefits of a multi-modal approach could lead to positive outcomes in populations known to have a greater risk for falling, such as the elderly population.

Eccentric exercise may also improve the passive stiffness of lower extremity extensors (Duclay & Pousson, 2008), which gives an additional rationale for the potential of eccentric exercise to reduce fall risk when combined with aquatic exercise. Lastly, there may also be an acute response to spinal reflex activity post-eccentric exercise, which could enhance the benefit of performing aquatic exercise if eccentric exercise is performed immediately prior. For example, a blunted proprioceptive spinal reflex response has been observed 24-48 hours post-eccentric exercise that may favor the activation of antagonist muscle groups (Hedayatpour, Arendt-Nielsen, & Falla, 2014). It is uncertain whether any spinal reflex alteration exists immediately post-eccentric exercise, yet a shift in relative activation favoring antagonist muscle groups could increase the therapeutic benefit of aquatic walking relating to improved foot clearance. Measuring muscle activation during land and aquatic walking pre- and post-eccentric exercise could provide insight into a mechanism to explore this indirectly.

To the best of our knowledge, there have been no studies that have compared muscle activity between walking in water and land environments before and after an applied bout of multi-joint lower-extremity eccentric exercise. This is a gap in the research that, when filled, may provide more insight into the mechanism behind the potential of a multi-modal approach toward improving gait abnormalities that relate to fall risk in older adults. Specifically, eccentric exercise, when combined with aquatic exercise, may be able to promote a more favorable balance between lower extremity flexor and extensor muscle activation, while also improving the ability to respond to perturbations via increased muscular strength and passive stiffness. Therefore, the purpose of this study was to analyze lower extremity muscle activation in a sample of young adults walking during water immersion and on land before and after eccentric exercise. This study may provide additional preliminary evidence that could support future research into a multi-modal approach for improving gait and reducing falls in vulnerable populations.

Methods

Participants

An a priori power analysis was conducted in G*Power using effect sizes from prior research (Long, 2023; $f = 0.3$, $\alpha = 0.05$, $\beta = 0.80$). It was determined that a minimum sample size of 24 participants was necessary to provide adequate statistical power. Thus, we recruited a convenience sample of 26 healthy, recreationally active adults (Table 1). All participants completed the protocol of the study in full. In this study, we defined recreationally active as being able to walk for at least 20 minutes without an assistive device. To be included in the study, participants had to be between the ages of 18-35 and meet the established criteria for recreational activity. Participants were excluded from the study if: (a) they reported a history of neurological disease expressing motor symptoms (e.g. stroke, multiple sclerosis, recent concussion, etc.), (b) they reported current physical discomfort or an injury that affects their ability to walk, (c) they reported having a surgical intervention on the lower limbs or trunk in the prior two years, and (d) reported having torn a hip, knee, or ankle ligament in the past 2 years. Written informed consent was obtained from all participants via signature on an informed consent document approved by the University institutional review board.

Table 1. Participant Characteristics.

Sex	n	Age (years)	Height (cm)	Body Mass (kg)	BMI
Total	26	21.6 (2.5)	176.4 (6.9)	75.9 (13.3)	24.2 (3.4)
Female	10	20.3 (2.2)	174.9 (4.4)	76.1 (10.9)	24.9 (3.3)
Male	16	22.4 (2.4)	177.3 (8.2)	75.7 (14.9)	24.1 (3.5)

Data are reported as mean (SD). BMI = body mass index.

Experimental Design

This study utilized a cross-sectional, repeated-measures research design comparing within-subjects differences in TA, GM, BF and VL muscle activity during walking on land and in water, both prior to and immediately following a single bout of lower extremity multi-joint eccentric exercise. Each participant performed both the water and land trials and served as their own control. This allowed control for inter-subject variability and allowed for better comparison of sEMG signals.

Instruments

Land trials were performed on a Tandem Treadmill (AMTI, Watertown, MA, USA) that was located in a Motion Analysis Laboratory, while aquatic trials were performed in a HydroWorx 2000 Series pool (HydroWorx, Middletown, PA, USA). The HydroWorx pool contains an 8 x 12-ft underwater treadmill platform with variable floor depth. The water temperature was maintained at 29.5°C ± 0.2°C, a thermoneutral range for aquatic exercise (McArdle et al., 1992). Participants were submerged to the level of the xiphoid process during aquatic trials. Previous studies have shown that this depth is optimal for minimizing float time during the non-contact phase of the stride cycle (Rutledge et al., 2007).

Muscle activity of the TA, GM, BF and VL were recorded using a 16-channel waterproof sEMG system (Cometa Mini Wave, Cometa SRL, Milan, Italy). The raw sEMG signals were collected at 2000 Hz (Silvers et al., 2014). Video data were captured from the sagittal-plane view at 100 Hz using an underwater camera (Miqus Underwater, Qualisys AB, Sweden) and synchronized with sEMG recordings. Eccentric exercise was facilitated through a multi-joint eccentric dynamometer (Eccentron, BTE Technologies, Hanover MD).

Procedures

Participants underwent a separate familiarization session before experimental testing to acclimate to the multi-joint eccentric dynamometer and aquatic treadmill. Familiarization began with eccentric training performed at a submaximal 40% load for 3 minutes to best simulate the following experimental session. The 40% submaximal load was established by having participants perform an initial maximal eccentric strength test on the Eccentron. After the participant underwent familiarization with the Eccentron, they proceeded to a familiarization of walking on the aquatic treadmill. Participants were asked to walk at a speed of 2.5 mph. Participants walked for a minimum of 3 minutes. Familiarization was considered successful when participants achieve walking at a “normal” gait which can be defined as walking similarly underwater as they would on land. This was determined by observing the participants' gait using the cameras in the underwater treadmill. Anthropometric data including height, weight, and BMI were also collected during the familiarization session.

The experimental testing for each participant was completed in a single session at least 72 hours after the familiarization session. To begin, electrode sites were shaved, cleaned with an alcohol swab, and adhesive waterproof electrodes were then placed over the TA, GM, BF and VL of the dominant leg according to guidelines established by the Surface Electromyography (sEMG) for Non-Invasive Assessment of Muscles (SENIAM) project (Hermens et al., 2000). Adhesive, hypoallergenic waterproof wrapping was used to further secure the electrodes in an effort to minimize movement artifacts in the sEMG signals. The dominant leg was defined as the leg with which the participant responded that they would kick a ball. In the experiment, participants walked for 2-min at 2.5 mph on land and in water before and after a 3-minute bout of eccentric exercise (12-min total walk time) while sEMG data was collected. Walk speeds were determined based on previous literature which suggests that the selected speed of 2.5 mph required the participants to walk at a quicker gait while also maintaining the pendulum gait characteristics of walking (Long, 2023). The land trial was performed first to prevent thermoregulatory effects on muscle activation occurring after the water immersion and to prevent sEMG electrodes from disconnecting as a result of participants drying off from the water condition. Participants were submerged to the level of the xiphoid process during the aquatic walking trials. For the aquatic trials, participants were instructed to walk as they would on land to minimize float time. Additionally, no arm swimming was allowed. Participants wore a swimsuit or compression shorts and walked barefoot during the water trials but wore athletic shoes during the land trials.

Data Reduction

Ten full stride cycles from the last 30 seconds of each trial were selected for analysis. A full stride cycle was defined as the time duration between two subsequent foot strikes with the dominant foot. Time points corresponding with the beginning and ending of the stance and swing phases were determined using frame-by-frame video analysis. Stance was defined as foot strike to toe-off, and swing was defined as toe-off to foot strike.

Data Processing and Analysis

sEMG signals were processed in MATLAB (the Mathworks Inc., Natick, MA, USA). sEMG signals were passed through a 4th order recursive Butterworth filter (10-500 Hz) to reduce signal drift and high frequency noise. Muscle activation magnitudes for each swing and stance phase were estimated by taking the root mean square (RMS) of filtered sEMG signals. RMS activation magnitudes were averaged across 10 stride cycles, with mean values for the swing and stance phases passed on for statistical analysis. Co-activation (Co-A) indices for both stance and swing phases in each condition were estimated by taking a linear ratio of antagonist to agonist activation magnitude. There were two separate Co-A measures, Co-A of the shank (lower-leg muscles) and Co-A of the thigh (thigh muscles).The TA and the VL were considered the agonists during the swing phase and antagonists during the stance phase, while the GM and BF were considered the agonists during the stance phase and the antagonists during the swing phase. Lastly, kinematic variables including stance time (s), swing time (s), stride length (m), and stride rate (strides/s) were computed and averaged across the 10 stride cycles for each condition. Mean values for kinematic and sEMG variables were passed on for statistical analysis.

Statistical Analysis

All statistical procedures were performed using RStudio (Version 4.3.3). Intraclass correlation coefficients (ICC) and their 95% confidence intervals (95% CI) were used to assess the inter-trial reliability of sEMG measures. ICCs were constructed using a single measure, absolute agreement, 2-way mixed effects model. For all dependent measures, main effects and interactions between environment (land × water) and eccentric exercise (Pre-Eccentric × Post-Eccentric) were evaluated using a 2-way within-subjects repeated measures analysis of variance (RMANOVA). All hypothesis tests were conducted using an alpha type I error threshold of 0.05.

ICC values were classified as excellent reliability (>0.90), good reliability (0.75-0.90), moderate reliability (0.50-0.75), or poor reliability (<0.50) (Koo & Li, 2016).

Results

Inter-trial Reliability

The inter-trial reliability of measures was moderate to excellent, with exception of stance phase Co-A Shank during pre-eccentric land walking, stance phase Co-A Shank during water walking, and swing phase Co-A Shank during pre-eccentric water walking (*F* = 4.7– 583.0, *p* <0.001; See Tables 2-5).

Table 2. Inter-trial reliability of land measures during the stance phase.

Measure	Pre-Eccentric	Post-Eccentric
Stance time (s)	0.851 (0.770-0.918)	0.812 (0.714-0.896)
TA RMS (μV)	0.681 (0.548-0.812)	0.716 (0.589-0.835)
GM RMS (μV)	0.843 (0.756-0.914)	0.862 (0.784-0.926)
VL RMS (μV)	0.664 (0.528-0.800)	0.980 (0.966-0.990)
BF RMS (μV)	0.944 (0.907-0.971)	0.979 (0.965-0.989)
Co-A Shank (%)	0.261 (0.143-0.442)	0.631 (0.490-0.776)
Co-A Thigh (%)	0.631 (0.490-0.776)	0.631 (0.490-0.777)

Data are presented as ICC estimate (95% confidence interval). TA = tibialis anterior; GM = medial gastrocnemius; VL = vastus lateralis; BF = biceps femoris; RMS = root-mean-square; Co-A = co-activation.

Table 3. Inter-trial reliability of water measures during the stance phase.

Measure	Pre-Eccentric	Post-Eccentric
Stance time (s)	0.794 (0.690-0.885)	0.772 (0.660-0.872)
TA RMS (μV)	0.683 (0.55-0.813)	0.725 (0.601-0.841)
GM RMS (μV)	0.585 (0.44-0.742)	0.539 (0.392-0.706)
VL RMS (μV)	0.740 (0.62-0.851)	0.983 (0.972-0.991)
BF RMS (μV)	0.781 (0.672-0.877)	0.802 (0.700-0.890)
Co-A Shank (%)	0.421 (0.278-0.605)	0.422 (0.279-0.606)
Co-A Thigh (%)	0.571 (0.425-0.731)	0.558 (0.411-0.721)

Data are presented as ICC estimate (95% confidence interval). TA = tibialis anterior; GM = medial gastrocnemius; VL = vastus lateralis; BF = biceps femoris; RMS = root-mean-square; Co-A = co-activation.

Table 4. Inter-trial reliability of land measures during the swing phase.

Measure	Pre-Eccentric	Post-Eccentric
Swing time (s)	0.763 (0.651-0.864)	0.787 (0.680-0.881)
TA RMS (μV)	0.725 (0.600-0.841)	0.915 (0.862-0.955)
GM RMS (μV)	0.627 (0.486-0.774)	0.923 (0.875-0.960)
VL RMS (μV)	0.678 (0.544-0.81)	0.964 (0.940-0.981)
BF RMS (μV)	0.878 (0.807-0.935)	0.970 (0.950-0.985)
Co-A Shank (%)	0.609 (0.466-0.761)	0.776 (0.666-0.874)
Co-A Thigh (%)	0.769 (0.657-0.870)	0.746 (0.627-0.855)

Data are presented as ICC estimate (95% confidence interval). TA = tibialis anterior; GM = medial gastrocnemius; VL = vastus lateralis; BF = biceps femoris; RMS = root-mean-square; Co-A = co-activation.

Table 5. Inter-trial reliability of water measures during the swing phase.

Measure	Pre-Eccentric	Post-Eccentric
Swing time (s)	0.868 (0.792-0.929)	0.812 (0.714-0.896)
TA RMS (μV)	0.846 (0.76-0.916)	0.886 (0.819-0.939)
GM RMS (μV)	0.503 (0.356-0.677)	0.525 (0.378-0.695)
VL RMS (μV)	0.539 (.392-0.706)	0.987 (0.977-0.993)
BF RMS (μV)	0.692 (0.561-0.819)	0.934 (0.891-0.965)
Co-A Shank (%)	0.487 (0.341-0.663)	0.703 (0.574-0.827)
Co-A Thigh (%)	0.580 (0.434-0.739)	0.836 (0.747-0.910)

Data are presented as ICC estimate (95% confidence interval). TA = tibialis anterior; GM = medial gastrocnemius; VL = vastus lateralis; BF = biceps femoris; RMS = root-mean-square; Co-A = co-activation.

ANOVA

Interactions

Central tendency and dispersion results for dependent measures are presented in Table 6. A significant environment × eccentric exercise interaction was observed for Thigh Co-A during swing ($F = 5.4$, $p < 0.001$; Table 6). Post-hoc analysis for the Thigh Co-A during swing revealed that muscle activation was significantly greater for post-eccentric land walking compared to pre-eccentric land walking ($p = 0.005$). Thigh Co-A during swing was significantly lower for both pre- and post-eccentric water walking relative to post-eccentric land walking ($p < 0.001$). Lastly, Thigh Co-A was also significantly lower for pre-eccentric water walking relative to pre-eccentric land walking ($p = 0.014$). The environment × eccentric exercise interaction on VL RMS Swing approached significance (*F* = 3.4, *p* = 0.067), yet no other significant environment × eccentric exercise interactions were observed (*F* = 0.1 – 0.9, *p* = 0.245 – 0.822).

Table 6. Central tendency and dispersion results.

Measure	Land Pre	Land Post	Water Pre	Water Post
Stance time (s)	0.75 (0.04)	0.73 (0.04)	0.80 (0.06)	0.80 (0.07)
Swing time (s)	0.40 (0.03)	0.41 (0.03)	0.66 (0.08)	0.69 (0.07)
Stride length (m)	1.28 (0.06)	1.28 (0.06)	1.63 (0.14)	1.67 (0.14)
Stride rate (strides*s^{-1})	0.87 (0.04)	0.88 (0.04)	0.69 (0.05)	0.67 (0.06)
TA RMS Stance (µV)	62.4 (21.8)	64.7 (22.0)	51.9 (18.0)	51.6 (20.1)
GM RMS Stance (µV)	85.9 (30.3)	83.6 (37.1)	55.3 (22.1)	56.3 (23.7)
VL RMS Stance (µV)	22.3 (12.4)	22.3 (12.4)	17.6 (7.8)	16.1 (7.2)
BF RMS Stance (µV)	26.4 (24.3)	23.57 (12.8)	36.4 (20.3)	39.0 (21.9)
TA RMS Swing (µV)	78.9 (22.8)	71.3 (33.5)	93.0 (26.8)	99.5 (38.1)
GM RMS Swing (µV)	15.6 (12.1)	14.6 (8.3)	11.0 (5.5)	11.0 (7.9)
VL RMS Swing (µV)	15.9 (11.7)	10.4 (7.7)	18.7 (5.8)	19.4 (7.3)
BF RMS Swing (µV)	34.8 (21.6)	33.4 (18.8)	37.8 (24.5)	33.6 (18.8)
Co-A Shank Stance (%)	74.9 (31.2)	86.3 (41.6)	108.0 (42.3)	106.9 (49.5)
Co-A Thigh Stance (%)	94.6 (41.2)	91.0 (53.7)	66.6 (45.1)	75.3 (63.9)
Co-A Shank Swing (%)	19.3 (14.2)	22.9 (18.7)	14.7 (13.0)	13.0 (14.2)
Co-A Thigh Swing (%)	278.8 (134.1)	426.9 (234.3)[a]	170.9 (74.8)[ab]	182.7 (107.8)[b]

TA = tibialis anterior; GM = medial gastrocnemius; VL = vastus lateralis; BF = biceps femoris; RMS = root-mean-square; Co-A = co-activation. [a]Significantly different from Land Pre (*p* < 0.05). [b]Significantly different from Land Post (*p* < 0.05).

Main Effects

Main effects of environment were observed across all measures (*F* = 4.5 – 602.6, *p* <0.001 – 0.036; Table 7) with the exception of BF RMS during the swing phase (*F* = 0.2, *p* = 0.699; Table 7). Stance time (*F* = 35.3, *p* < 0.001), Swing time (*F* = 602.6, *p* < 0.001), Stride length (*F* = 314.9, *p* < 0.001), BF RMS Stance (*F* = 10.2, *p* = 0.002), TA RMS Swing (*F* = 12.2, *p* < 0.001), VA RMS Swing (*F* = 12.9, *p* < 0.001) and Co-A Shank Stance (*F* = 10.8, *p* = 0.001) increased from the effect of water immersion (collapsed across pre- and post-eccentric exercise time points). Stride rate (*F* = 406.6, *p* < 0.001), TA RMS Stance (*F* = 6.8, *p* = .011), GM RMS

Stance ($F = 26.1$, $p < 0.001$), VL RMS Stance ($F = 4.5$, $p = 0.036$), GM RMS Swing ($F = 5.7$, $p = 0.0189$), Co-A Thigh Stance ($F = 4.6$, $p = 0.034$), Co-A Shank Swing ($F = 5.9$, $p = 0.017$) and Co-A Thigh Swing ($F = 35.8$, $p < 0.001$) decreased from the effect of water immersion.

A significant main effect of eccentric exercise was observed for Co-A Thigh during the swing phase ($F = 7.4$, $p = 0.008$), with greater Thigh Co-A observed post-eccentric exercise (collapsed across environment). There were no other main effects of eccentric exercise on dependent measures ($F = 0.0 – 2.1$, $p = 0.154 – 0.929$).

Table 7. Central tendency and dispersion results collapsed across pre- and post-eccentric exercise.

Measure	Land	Water
Stance time (s)	0.74 (0.04)	0.80 (0.06)^a
Swing time (s)	0.41 (0.03)	0.68 (0.07)^a
Stride length (m)	1.28 (0.06)	1.65 (0.14)^a
Stride rate (strides*s^{-1})	0.87 (0.04)	0.68 (0.06)^a
TA RMS Stance (μV)	61.8 (20.1)	51.8 (18.9)^a
GM RMS Stance (μV)	84.8 (33.6)	55.8 (22.7)^a
VL RMS Stance (μV)	21.1 (12.0)	16.9 (7.5)^a
BF RMS Stance (μV)	25.0 (19.3)	37.7 (20.9)^a
TA RMS Swing (μV)	75.1 (28.6)	96.3 (32.8)^a
GM RMS Swing (μV)	15.1 (10.3)	11.0 (6.8)^a
VL RMS Swing (μV)	13.1 (10.2)	19.1 (6.5)^a
BF RMS Swing (μV)	34.1 (20.0)	35.7 (21.7)
Co-A Shank Stance (%)	80.6 (36.9)	107.4 (25.6)^a
Co-A Thigh Stance (%)	92.8 (47.4)	70.9 (54.9)^a
Co-A Shank Swing (%)	21.1 (16.5)	13.8 (13.5)^a
Co-A Thigh Swing (%)	353.9 (203.3)	176.8 (92.1)^a

TA = tibialis anterior; GM = medial gastrocnemius; VL = vastus lateralis; BF = biceps femoris; RMS = root-mean-square; Co-A = co-activation. ^{a}Significantly different from Land ($p < 0.05$).

Table 8. Central tendency and dispersion results collapsed across environment.

Measure	Pre-Eccentric	Post-Eccentric
Stance time (s)	0.77 (0.06)	0.77 (0.06)
Swing time (s)	0.53 (0.14)	0.55 (0.15)

Stride length (m)	1.46 (0.21)	1.47 (0.22)
Stride rate (strides*s^{-1})	0.78 (0.10)	0.78 (0.11)
TA RMS Stance (μV)	55.4 (18.1)	58.2 (21.9)
GM RMS Stance (μV)	70.6 (30.5)	69.9 (33.7)
VL RMS Stance (μV)	19.9 (10.5)	18.0 (9.8)
BF RMS Stance (μV)	31.4 (22.7)	31.3 (19.4)
TA RMS Swing (μV)	86.0 (25.6)	85.4 (38.3)
GM RMS Swing (μV)	13.3 (9.6)	12.8 (8.3)
VL RMS Swing (μV)	17.3 (9.3)	14.9 (8.7)
BF RMS Swing (μV)	36.3 (22.9)	33.5 (18.6)
Co-A Shank Stance (%)	91.4 (40.4)	96.6 (46.5)
Co-A Thigh Stance (%)	80.6 (45.1)	83.1 (59.0)
Co-A Shank Swing (%)	17.0 (13.7)	17.9 (17.2)
Co-A Thigh Swing (%)	224.9 (120.6)	304.8 (218.7)^{a}

TA = tibialis anterior; GM = medial gastrocnemius; VL = vastus lateralis; BF = biceps femoris; RMS = root-mean-square; Co-A = co-activation. ^{a}Significantly different from Pre-Eccentric ($p <$ 0.05).

Discussion

The purpose of this study was to compare lower-limb muscle activation during gait, performed in water versus on land, before and after a short bout of eccentric exercise, in order to provide evidence for the potential of a multi-modal approach toward improving gait abnormalities that relate to fall risk in older adults.

The significant differences in TA and GM muscle activation observed between land and water in the present study are consistent with previous aquatic literature (Long, 2023). For instance, TA RMS during the swing phase increased by 28% (Cohen's d = 0.69), while GM RMS during swing was reduced by 27% (Cohen's d = -0.48) when walking was performed in water compared to on land. Together, these findings provide explanation for the observed 35% reduction in Co-A of the lower leg during the swing phase of water walking (Cohen's d = -0.49). Moreover, TA RMS during the stance phase was reduced by 16% (Cohen's d = -0.51), yet this was observed concurrently with a 34% reduction in GM RMS during stance (Cohen's d = -1.03), leading to the observation of a 33% increase in Co-A of the lower leg during stance (Cohen's *d* = 0.86). Results for both stance and swing phase favor TA activity relative to GM activity between environments. There were no significant differences in TA or GM muscle activity between pre- and post-eccentric exercise across both environments (Table 8), which may have been influenced, in part, by the multi-joint isokinetic dynamometer facilitating greater eccentric loading on the quadriceps muscle group relative to the plantar flexors (Petrofsky et al., n.d.).

While the results for the lower leg were anticipated based on the findings of Long (2023), the outcomes for thigh muscle activation did not follow the same pattern, leading to several intriguing findings. Similar to the TA, VL RMS was reduced by 20% during the stance phase (Cohen's *d* = -0.43) and increased by 46% during the swing phase (Cohen's *d* = 0.72) when walking was performed in water vs. land. This may be explained by increased fluid resistance in water opposing knee extension during swing and a reduction in apparent body weight due to buoyancy during stance. BF RMS, however, was 51% greater during the stance phase of water walking (Cohen's *d* = 0.63), which contributed to the observation of a 24% reduction in thigh Co-A during stance (Cohen's *d* = -0.43). Thus, the significant increase in BF RMS during the stance phase appeared to invert the effect of water immersion on thigh Co-A during stance, compared to the observed increase in shank Co-A during stance. Greater BF but lower GM activity during stance could be a result of the GM having a greater role in counteracting body weight to maintain an upright posture in comparison to the BF. It can be interpreted that the offloading effect of buoyancy led to a reduction in GM activity, but fluid resistance may have led to an increase in BF activity.

Co-A of the thigh and shank were both lower during the swing phase of water walking; however, a significant environment × eccentric exercise interaction on thigh Co-A revealed a significant post-eccentric exercise increase for land walking exclusively. This finding may have been influenced by an interaction on swing phase VL RMS that approached significance. More specifically, swing phase VL RMS during land walking was reduced by 20% (Cohen's $d = -0.43$) following eccentric exercise. Although the interaction was not statistically significant given the alpha threshold used in the current investigation, a drop in VL activation could be due to muscular fatigue post-eccentric exercise. As previously mentioned, the isokinetic dynamometer used to facilitate eccentric exercise applies a much larger eccentric load on the thigh compared to the lower leg, as it involves a leg press motion similar to a traditional squat. During a squat, the GM is most active during the concentric portion of the movement, especially as squat depth increases (Caterisano et al., 2002). However, the eccentric dynamometer removes the concentric portion of the press motion, thereby likely reducing the level of GM activity. During a squat motion the TA is the primary dorsiflexor and contributes to ankle stability. Previous literature has established that muscle activity in the TA remains consistent throughout the ankle flexion angle of a squat (Bae et al., 2015). Therefore, it can be extrapolated that during the lengthening phase of the eccentric dynamometer, the TA likely does not experience significant changes in muscle activity. It should be noted that the VL resists the movement of the eccentric dynamometer as the knee goes into flexion. It is uncertain as to the eccentric loading of the BF during this motion, considering that the BF shortens during knee flexion and lengthens during hip flexion. It is likely that the BF is not as active as the VL during the multi-joint eccentric exercise task performed on the Eccentron.

The findings of this study demonstrate the need for additional research into the applicability of aquatic and eccentric exercise as a multi-modal approach for reducing fall risk and improving walking gait. The observation of a single significant environment × eccentric exercise interaction does not diminish the potential benefits of combining eccentric exercise with aquatic treadmill exercise to possibly promote greater muscle strength and improved gait mechanics. For instance, the results of this study indicate that eccentric exercise can be combined with aquatic walking in young adults without disruption of stride kinematics and with minimal disruption to lower-extremity muscle activation. It may be beneficial for future research to examine muscle activation and gait mechanics within a longitudinal study design to truly analyze the effectiveness of a formal multi-modal training program involving eccentric exercise and water walking. Future research could also focus more on a targeted population aside from young adults that may stand to benefit more from a combined eccentric and aquatic exercise training approach. Also, further research is needed to identify optimal training parameters, which include population specific duration and resistance for eccentric exercise in addition to aquatic walking speed, duration, and jet resistance.

Limitations

A convenience sample of healthy, recreationally active adults was selected to conduct a preliminary comparison of lower extremity muscle activity between land and water environments before and after a bout of eccentric exercise. Given that the purpose of this study was to explore the potential application of eccentric exercise and aquatic treadmill walking as a multi-component approach to reducing fall risk in older populations, future studies may consider sampling from populations known to have a greater risk for falling and gait dysfunction.

Limitations involving sEMG should be considered when interpreting the findings of this study. Due to using BMI as a criterion for participation, this study may not fully account for the potential influence of subcutaneous fat on sEMG signal strength. Utilizing a body composition test that includes measurements of leg fat might offer a more accurate indicator of whether individuals have optimal levels of subcutaneous fat to be included in the study. Furthermore, transitioning from aquatic to land environments and conducting a walking test before and after eccentric exercise could introduce movement artifacts or cause transitory displacement of sEMG electrodes.

Conclusions

The purpose of this study was to compare lower-limb muscle activation during gait, performed in water versus on land, before and after a short bout of eccentric exercise, in order to provide evidence for the potential of a multi-modal approach toward improving gait abnormalities that relate to fall risk in older adults. Evidence was found that eccentric exercise can be combined with aquatic walking without disruption of stride kinematics and with minimal disruption to lower-extremity muscle activation. This could prove to be beneficial in being able to apply eccentric exercise as a form of resistance training without affecting gait when concurrently performing aquatic treadmill walking. The findings are particularly relevant to clinical populations that may stand to benefit from both improved lower-extremity muscle strength and gait characteristics known to associate with fall risk. However, additional research is needed to explore whether the effects of environment and eccentric exercise are consistent in populations outside of healthy, recreationally active young adults.

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