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RELATIONSHIP OF ECCENTRIC STRENGTH AND FORWARD PERTURBATION RESTABILIZATION AFTER FOOT CONTACT

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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Abstract

Background: Forward falls are the most common fall direction and pose safety concerns for adults. To prevent forward falls, compensatory steps, and change-in-support reactions (e.g., foot contact) are critical for restabilizing center of mass after unpredictable, balance disturbances. Multi-joint, lower limb eccentric and isometric strength may provide additional insight on foot contact responses after a forward, temporally unpredictable perturbation. Multi-joint, eccentric muscular contractions have been found to result in significant neuromuscular adaptations (e.g., hypertrophy and muscular strength) and have higher retention capabilities than concentric contractions. Due to the importance of muscular strength in balance recovery, eccentric muscular strength could provide a new insight into improving future fall prevention programs. The primary aim of our investigation was to determine the relationship between restabilization after foot contact, age, and self-reported physical activity in response to a forward, temporally unpredictable perturbation and multi-joint muscular strength in the lower limbs. We hypothesized that adults who were faster at restabilizing after foot contact (e.g., time to restabilize), would produce greater multi-joint eccentric and/or isometric peak force. Our secondary aim was to assess the mean difference between preferred and non-preferred limb time to restabilize. We hypothesized that adults would restabilize faster on their preferred limb compared to non-preferred limb.

Research Question: Are adults with a greater capacity to restabilize after foot contact (time to restabilize) able to produce greater multi-joint eccentric and/or isometric peak force?
Our central hypothesis was that adults who have a greater capacity to restabilize after foot contact, or time to restabilize, would produce greater multi-joint eccentric and/or isometric peak

force. Do adults restabilize faster on their preferred limb compared to their non-preferred? Our secondary hypothesis was that adults would restabilize faster on their preferred limb compared to non-preferred limb.

Methods: Our sample consisted of 30 adults (31.2 ± 12.1 years, range: 18-58). Participants performed two blocks of 12 trials of forward, temporally unpredictable perturbation trials on both their preferred and non-preferred stepping limbs followed by assessments of multi-joint eccentric and isometric strength. Multivariate, linear regressions were used to evaluate the relationships and trends among variables. A paired-samples t-test was conducted to assess the mean differences between preferred and non-preferred limb time to restabilize.

Results: Individual multiple linear regression analyses indicated that neither multi-joint eccentric ($r = 0.385$, $p = 0.308$) nor isometric ($r = 0.317$, $p = 0.519$) strength had a significant impact on restabilization time in response to a forward perturbation in our sample of adults. A paired-sample t-test indicated no mean difference between preferred limb and non-preferred limb time to restabilize ($t\,(28) = 0.980$, $p = 0.335$).

Significance: Eccentric and isometric multi-joint lower body strength was not a performance predictor for restabilization time to a forward perturbation. Additionally, restabilization time did not differ between limbs. Future work will investigate the impact of lower limb multi-joint eccentric rate of force development as well as surface electromyography to assess whether these measures provide additional insight on forward step restabilization.

Introduction

The World Health Organization stated as of April 2021, 37.3 million falls that cause injury requiring medical attention occur per year and that falls are the second leading cause of "unintentional injury deaths" globally (*Falls* 2021). One way to address falls is change-in-support reactions, such as compensatory stepping and/or grasping reactions. In fact, it has been found that recovery from a large perturbation can only be addressed by change-in-support reactions (Maki & McIlroy, 1997). Stepping reactions increase the base of support further increasing the range of the center of mass displacement that can be reached before loss of stability results (Maki & McIlroy, 1997), and therefore could positively impact forward falls, the most common fall direction, in all ages (Stevens et al., 2014; Bosqueé et al., 2021).

Understanding the mechanisms involved in forward fall stability recovery across a wide range of ages can provide critical insight into reducing and/or avoiding future falls (Bosqueé et al., 2021). To reduce forward falls, compensatory steps and reactive balance control are critical for restabilizing center of mass after unexpected balance disturbances (Carty et al., 2015; Saumur et al., 2021). There is a coordination of neurophysiological mechanisms required for balance control (e.g., anticipatory posture adjustment, reactive posture adjustment, dynamic gait) (Chen et al., 2021). It has been found that spatio-temporal parameters, like long-term step width, are more variable when anticipating a perturbation (Nestico et al., 2020). Parameters that have been found to best demonstrate reactive balance performance are those derived from center of pressure (COP), which can be defined as the center point of the entire pressure of the foot-ground reaction force (Chen et al., 2021). Specifically, COP velocity has been found to be associated between balance control during quasi-static and dynamic phases of reactive stepping further indicating that COP variables composed of both spatial and temporal properties (e.g., COP velocity) could suggest the level of balance control during restabilization from quasi-static balance tasks (Tanel et al., 2018). Moreover, COP can be assessed in the anteroposterior (AP) and mediolateral (ML) directions, both of which are relevant in reactive stepping literature.

Bosqueé et al. (2021) reported that forward recovery stepping (examined by single versus multi-stepping) examined with lean and release tasks, a common tool used in perturbation-based training, was predictive of future fall risk. As previously mentioned, all ages are susceptible to forward falls, but concern increases with age. When examined in older adults, Singer et al. (2019) suggested that forward step instability persisted after perturbation-based training and that muscle force production of the lower limbs may have a role in after foot contact restabilization. Nagano et al. (2015) found that individuals taking single steps had greater eccentric power absorption and increased maximal knee flexion following heel contact. Moreover, Okubo et al. (2021) found that adequate isometric muscle strength was necessary to recover from balance disturbances as well as avoid future falls. Similar findings show that lower limb strength is a limiting factor in balance recovery after tripping and that balance recovery improved after just three weeks of perturbation-based training coupled with dynamic stability training when compared to a control group, suggesting the importance that lower limb strength could play in improvements of fall risk factors (Pijnapples et al., 2008). In addition, insufficient preparatory lower limb muscle activation may have an important role in reducing impact forces and maintaining stability and appears to contribute to stability control for older adults (Singer et al., 2019). Therefore, increasing lower limb muscle activation prior to step off could reduce impact forces, thus improving restabilization after a forward perturbation in older adults.

To reduce step impact forces and maintain stability, assessing and training lower body multi-joint strength-based capacities via eccentric exercise could be an advantageous approach

(Sanders, O.P., 2018) as a means to effectively improve one's absorbing of the downward falling momentum (Nagano et al., 2015). During eccentric contractions, both active and passive muscle properties promote high intrinsic muscle forces due to overloading of the muscle-tendon units, which can result in significant neuromuscular adaptations such as hypertrophy and muscle strength (Farthing and Chilibeck, 2003; Reeves et al., 2009; Roig et al., 2009). Additionally, eccentric muscular strength preservation has been found to be ~21% greater than concentric muscular strength in older adults (Roig et al., 2010). This suggests that the benefits associated with our ability to retain eccentric muscular strength gains can perhaps be maximized for a longer period of time across the latter part of our lifespan, potentially with a relatively lower training dose (Harper & Thompson, 2021).

Different methods have been used to assess eccentric muscular strength ranging from common methods like the NordBoard (Claudino et al., 2021) to seated isokinetic dynamometers such as the Eccentron, a multi-joint eccentric-based negative resistance training device (BTE Technologies, Hanover, MD, USA). Different from a single-joint dynamometer, the multi-joint capabilities of devices such as the Eccentron have the advantages of minimizing peak forces on a single joint as well as having more functional relevance of the multi-joint movement patterns, while retaining the ability to control the velocity of movement (i.e., isokinetic) which allows researchers to get highly controlled and quantifiable variables from standardized assessment (Harper & Thompson, 2021).

Understanding the relationship between lower limb eccentric muscular strength and forward perturbation after foot contact restabilization (specifically the AP COP component) could help identify a potential mechanistic connection, which could positively impact future fall prevention interventions. Moreover, self-reported physical activity and age should be explored as these variables could affect restabilzation following a forward perturbation. It has been found that adults with self-reported physical activity levels considered “inactive” score significantly higher on a Timed Up and Go Test, which is associated with increased fall risk (Silva et al., 2017). Additionally, deteriorations in leg strength may affect the ability to recover from unexpected perturbation have been found with aging (Bosquée et al, 2021; Pijnapples et al., 2008).

To our knowledge, no previous literature has assessed the relationship of time to restabilize and lower body multi-joint eccentric or isometric peak forces, therefore we proposed a cross-sectional design examining AP COP using force plates and a lean and release technique (Thelen et al., 2000) and multi-joint eccentric and isometric peak force of the lower limbs using a modified Eccentron device in a healthy adult population. The primary aim was to determine the relationship between restabilization after foot contact in response to a forward perturbation and multi-joint eccentric and isometric muscular strength in the lower limbs. We hypothesized that adults more efficient at restabilizing after foot contact (less time to restabilize, as defined by AP COP velocity), would produce greater multi-joint eccentric and/or isometric peak force. Our secondary aim was to assess the mean difference between preferred and non-preferred time to restabilize. We hypothesized that adults would restabilize faster on their preferred limb compared to non-preferred limb.

Methods

Participants

Thirty-three healthy adults (age 18-59) were initially recruited to evaluate their multi-joint eccentric and isometric strength and their ability to restabilize following a forward fall.

These individuals were recruited from the Cache Valley, UT area through indirect and direct contact recruitment methods. Interested individuals completed a pre-screening interview that determined their participation eligibility requiring them to be between 18 – 59 years old, willing to participate, and having a self-reported fluency in English.

Exclusion criteria included the following: the use of an assistive device for walking, any absolute contraindication(s) to exercise training according to the American College of Sports Medicine guidelines, severe cardiac disease, myocardial infarction or stroke within the past year, known neuromuscular diseases, severe rheumatologic or orthopedic disease (e.g., awaiting joint replacement), active inflammatory disease, lower limb injuries (e.g., hip fracture, hip or knee replacement within one year), uncontrolled hypertension (> 150/90 mm Hg), and any other significant comorbid conditions that would impair the ability to participate in the exercise-based assessment. Participants deemed eligible based off the screening criteria were invited to an in-person screening visit.

Experimental Protocol

Data were collected in the Dennis Dolny Movement Research Clinic at Utah State University. Participants attended two, approximately 90-minute sessions separated by 4 – 23 days. Eligible participants provided written informed consent for the experimental protocol as approved by the Utah State University Institutional Review Board and the study was conducted in accordance with the Declaration of Helsinki. The following sections will be a brief overview of the procedures.

Procedures for visit one included a review of their medical history and physical activity. The medical history questionnaire determined any current and/or previous surgeries and medical issues. Participants were asked about current physical activity habits via the Global Physical Activity Questionnaire (G-PAQ) (Cleland et al., 2014). Additionally, participants completed the Waterloo Footedness Questionnaire (Elias et al., 1998), and the History of Falls Questionnaire (Talbot et al., 2005). To assess uncontrolled hypertension (> 150/90 mm Hg), resting blood pressure was measured. Participants were then familiarized with the lean and release paradigm, in which they performed multiple practice trials of reactive stepping, and the modified Eccentron device to assess multi-joint eccentric and isometric muscle strength, in which they performed a practice sub-maximal and maximal strength test.

On visit two, participants performed 12 perturbation trials in two separate block formats (preferred stepping limb, and non-preferred stepping limb, respectively) with a short 1-2 minute rest period in between blocks. This block order was randomized using a random number generator (random.org) and the order recorded in a password-protected Microsoft Excel file (Microsoft Corporation, Redmond, WA, USA). Following the 24 total perturbations, participants performed the testing on the modified Eccentron device.

Measures

Global Physical Activity Questionnaire

Physical activity was assessed via four categories (work, travel to and from places, recreational activities, and sedentary behavior). Both the work and recreational activity categories assessed the typical time per day (in minutes) and days per week of vigorous and moderate intensity activities in each specific category. This questionnaire has been found to be good to very good at reporting overall physical activity (r = 0.58-0.89) between 14 different studies with sample sizes ranging from 16 to 940 (Keating et al., 2019).

History of Falls

The History of Falls questionnaire in our sample of young to middle-aged adults assessed activities prior to falling, perceived causes (accidental or environmental), and resultant injuries based on work by Talbot et al. (2005). Participants who had fallen within the last year, were asked about the activities, causes and injuries associated with the fall to assess if the causes were factors associated with instability.

Waterloo Footedness Questionnaire-Revised

Lower limb dominance was assessed via the Waterloo Footedness Questionnaire-Revised (WFQ-R) (Elias et al., 1998). As a diagnostic tool, this twelve-question assessment is the preferred reporting method to assess participants' self-reported limb dominance and foot preference for both mobility and stabilizing tasks (Elias et al., 1998). Observed limb dominance was also assessed during the practice trials of the lean and release protocol to evaluate observed preferred stepping limb (van Melick et al., 2017). Participants were instructed to step and restabilize as quickly as possible during the practice trial. The stepping foot was not prompted. The limb chosen to step with was deemed the preferred limb, regardless of what preferred limb was determined from the Waterloo Footedness Questionnaire-Revised.

Lean and Release Assessment

Rapid step response was assessed utilizing a lean and release cable approach (Bolton & Mansour, 2020) following a temporally unpredictable, forward perturbation. This approach provides insight into participants' reactive, rapid step response. Multicomponent force plates

(Kistler Instrument Corp., Winterthur, Switzerland) were located directly under the participants left and right limbs, respectively, with a central force plate directly in front of the participants to capture the selection of the rapid step response recording COP. This lean and release paradigm (**Figure 1**) uses a cable system attached to a safety harness worn by the participants. Specifically, a safety cable is attached to the ceiling and acts as a failsafe to catch participants in case of an unsuccessful step response that could result in a slip, trip, or fall. Another cable was secured to the back of the safety harness, attached to a magnet release on a wall behind the participants. The magnet serves as a brace support, allowing the participant to safely lean forward before the start of each trial.

Participants were instructed to completely relax and let themselves lean into the main support cable and that when the magnet was released, they should step forward and take a single step to restabilize as quick as possible. For additional safety parameters, a secondary catch cable slightly longer than the main support cable was attached from the wall to the safety harness. For the first trial, participants were not instructed which foot to step with. The foot used to step with first was then deemed the preferred, stepping limb (Saumur et al., 2021). After each step response, participants were instructed to hold their stance and stabilize for approximately five seconds. A series of practice trials were performed with each limb prior to the 12 trials per limb (24 total trials).

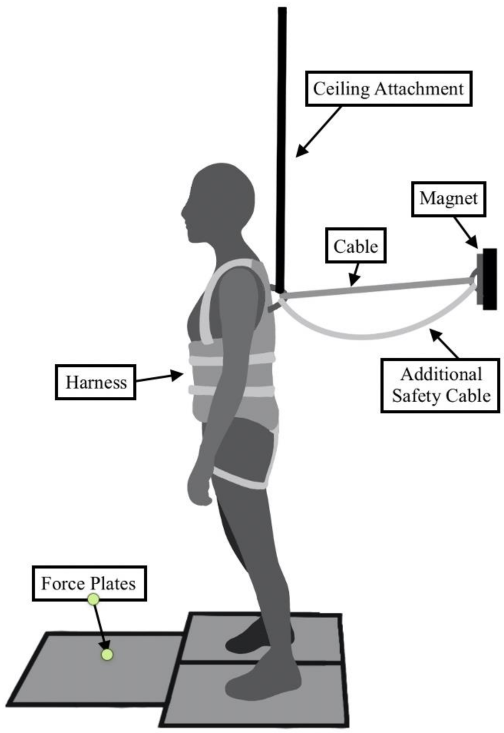

Figure 1. Lean and release paradigm. Adapted from Chan et al. (2019) our lean and release testing platform consists of three plates, a posterior ceiling attachment, and additional safety cable.

Force

Kistler force plates assessed COP after foot contact restabilization via AP COP velocity. Time to restabilization (presented in **Figure 2**) was evaluated using the following parameters: the time from foot contact to when the net AP COP velocity returned to within three standard deviations of the mean net AP COP velocity, compared to the last two seconds of foot contact (Saumur et al., 2021).

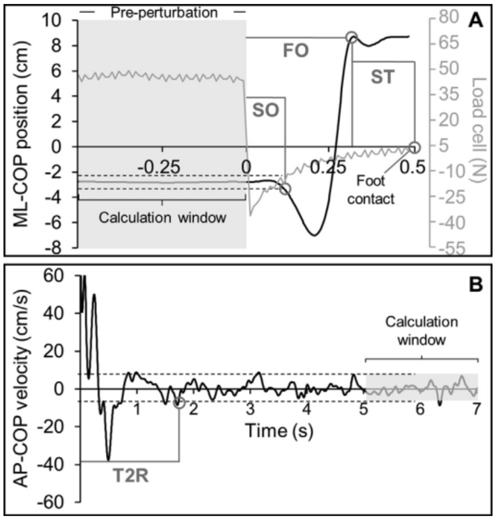

Figure 2. Originally presented in Saumur et al. (2020), this figure represents a reactive step response for a single participant. A) Represents the force plate measures prior to foot contact from ML COP position when time zero is perturbation onset indicated by the load cell dropping below 5 N. B) Represents the AP COP velocity following foot contact where restabilization is reached once the velocity remains within three standard deviations of the mean AP COP velocity for at least one second (time starts at foot contact). Abbreviations: SO, step onset; FO, foot-off; ST, swing time; T2R, time to restabilization.

Eccentron device

Multi-joint lower limb strength was assessed via isokinetic and isometric testing on the modified Eccentron device in which the raw, analog signals were exported to a Biopac data acquisition system (MP150WSW, Biopac Systems Inc., Santa Barbara, CA, USA). Participants performed multi-joint (involving the hip, knee, ankle) isokinetic and isometric extensions on a modified Eccentron machine (**Figure 3**). For isokinetic testing, participants performed 12, alternating eccentric contractions (six per limb) with the lower limbs with their knee joint moving from approximately 30° to 90°. A warm-up trial was conducted first in which participants were instructed to resist the alternating eccentric load of the machine at a “sub-maximal” effort for 12 contractions. For the maximal eccentric test, participants were instructed to resist the alternating eccentric load of the machine “as hard as you can” for all 12 contractions (Crane et al., 2020). Upon completing this test, the participant’s rating of perceived exertion category ratio scale was recorded according to the Borg Scale (Borg, 1998). This scale was provided in a visual format in which participants were instructed to rate their level of effort based on a scale from 0, representing “Nothing at all”, to 10, representing “Absolute Maximum Highest Possible”. A short 2-3 minute rest was provided before preceding to isometric testing.

For isometric testing, participants were seated upon the modified Eccentron device with their feet placed on the pedals and the seat positioned such that their extended knee was at approximately 30° of knee flexion (measured with a goniometer by an experienced member of the research team). They were instructed, on a researchers count, to push into the pedal with the single instructed limb maximally for three seconds. This was repeated on the other limb. One trial per limb was conducted with a short 1-2 minute rest between limbs.

The Eccentron was modified to be able to obtain the raw, analog signals via load cells from both the right and left pedals. Moreover, custom-made stopping blocks for each pedal were used exclusively for the isometric tests (to ensure no movement was allowed in the pedal system).

Figure 3. Multi-joint modified Eccentron illustration. Printed in Harper & Thompson (2021). The machine works by unilaterally moving the pedals towards the participant, in an alternating manner. The resisting force produced by the participant can be viewed on the screen. For this study, wires were connected from the front of the machine to a separate computer and the raw, analog signals were collected into the Biopac acquisition system for both isokinetic and isometric data collection. Additionally, two blocks were engineered to place under each pedal in order to perform isometric contractions.

Data Analysis

Data entry

Data recorded from the screening, demographics, questionnaires (e.g., G-PAQ, Waterloo Footedness and the History of Falls Questionnaires), and rating of perceived exertion were entered into Research Electronic Data Capture (REDCap), a secure web-based data entry system (Harris et al., 2009; Harris et al., 2019). Data was first entered by the primary researcher and then verified by a second researcher (C.O., S.A.H.). Once verified, all data was exported via Microsoft Excel CSV (Microsoft Corporation, Redmond, WA, USA) for analysis.

Data Acquisition Systems and Data Reduction

A BioWare® 5.4.3.0 data acquisition software (Kistler Instrument Corp., Winterthur, Switzerland) sampled COP (at 1000 Hz) across the three force plates. COP data was low pass filtered using a fourth order Butterworth filter and a low pass cut-off frequency of 30 Hz. Subsequent processing occurred through a custom written LabVIEW (LabVIEW 2016, National Instruments, Austin, TX, USA) program. Specifically, foot touchdown onto the front, central force plate was defined as the moment when vertical force was greater than 5 N. Time to restabilization was then calculated as the time from foot touchdown to the time at which the net AP COP velocity remained within three standard deviations of the mean net AP COP velocity during the last 2 seconds of foot contact (which was determined manually by an experienced investigator via visual inspection) for at least 1 second (Saumur et al., 2021).

A Biopac data acquisition system sampled raw force data while performing the isokinetic and isometric measures on the modified Eccentron device. Data were sampled at 2000 Hz and processed offline with custom written LabVIEW software. Raw, analog signals were then scaled to N through the following calculation:

$$Newtons = ((Vsignal - Vzero\_offset) * 4903.3) / 1.9937.$$

The signals were then gravity-corrected for limb weight (i.e., the baseline was set to zero), and filtered with a fourth-order, zero phase-shift, low-pass Butterworth filter with a 50 Hz cutoff (Thompson et al., 2018a). All isokinetic and isometric peak force values were normalized to body weight to account for the possible influence of body size on these strength variables (Thompson et al., 2013; Choquette et al., 2010). Preferred limb isokinetic and isometric peak forces normalized to body weight were used for subsequent data analysis.

Statistical Analysis

Descriptive statistics are reported as mean ± standard deviation. Paired samples t-tests were conducted to assess if there was a mean difference between preferred and non-preferred isokinetic and isometric peak force (both normalized to body weight). Pearson R correlations were conducted to assess the strength of the relationships among the variables of interest. Cohen's d effect sizes were calculated for each analysis and were assessed as follows: 0.0 – 0.2 representing a small effect size, 0.2 < effect size < 0.8 representing a medium effect size, and an effect size ≥ 0.8 representing a large effect size.

To assess the magnitude of the role of multi-joint eccentric and isometric peak force normalized to body weight, age, and reported physical activity in predicting the time to restabilize we conducted a logistic regression analysis. We proceeded with the rationale that one predictive variable can be assessed for every ten events for regression analysis (Moons et al., 2014; Moons et al., 2015; Pavlou et al., 2015). Therefore, 30 participants completed the proposed study design, utilizing three predicted variables. Primary outcomes assessed were multi-joint eccentric and isometric peak forces normalized to body weight, and AP COP velocity (e.g., time to restabilize).

Results

Table 1 presents the demographic data of the study participants. Thirty participants (age = 31 ± 12 years, 57% Female) completed both study visits. Three participants did not qualify (two exceeded the modified-Eccentron maximal force load (~750lbs.), and one exceeded the resting blood pressure assessment, (> 150/90 mm Hg). There were 720 trials conducted for the lean and release testing and 696 analyzed (24 trials were not saved for one participant (participant #5) due to an equipment error).

For the modified Eccentron device, there were 90 trials conducted and 89 trials analyzed in which the Biopac data acquisition system failed to save one left limb, isometric trial. The mean time between visits was 7.9 ± 3.9 days.

Table 1. Participants descriptive statistics (n = 30).

Age, years	31.2 ± 12.1
Weight (taken from force plate), kg*	81 ± 22.8
Sex	
Male	13 (43%)
Female	17 (57%)
Preferred stepping foot, % right	27 (88.3%)
Observed stepping foot, % right	26 (86.7%)

Moderate activity	
Days/week	2.7
Minutes/day	71.2
Vigorous activity	
Days/week	1.5
Minutes/day	32.7
Energy expenditure, METs/week	5723.3 ± 4400.3
Reported falls (in last year)	6 (20%)
During ambulation	2 (6.7%)
During sports	3 (10%)
During other specified activity	1 (3.3%)
Icy environment involved	4 (13.3%)
External forced involved	2 (6.7%)
Injury occurred	1 (3.3%)
No injury occurred	5 (16.7%)
RPE (multi-joint isokinetic test)	8 ± 2
Preferred, isokinetic peak force (normalized to body weight), N/kg	23.0 ± 6.7
Preferred, isometric peak force (normalized to body weight), N/kg	19.4 ± 7.6
Non-preferred, isokinetic peak force (normalized to body weight), N/kg	22.2 ± 6.3
Non-preferred, isometric peak force (normalized to body weight), N/kg	18.7 ± 8.2

The values presented are mean ± standard deviation or counts (percentages). *Weight was reported from n = 29. Preferred stepping foot was determined by the Waterloo Footedness Questionnaire. Observed stepping foot was determined as the foot stepped with during the first practice trial of the lean and release assessment. The Global Physical Activity Questionnaire surveyed self-reported moderate and vigorous activity. The History of Falls Questionnaire inquired about reported falls from in the last year. Abbreviations: MET, metabolic equivalent; RPE, rating of perceived exertion.

Paired-Samples T-test

A paired-samples t-test was used to determine whether there was a mean difference between the preferred limb compared to non-preferred limb for the time to restabilize. No outliers were detected that were more than 1.5 box-lengths from the edge of the box in a boxplot. The assumption of normality was not violated as assessed by Shapiro-Wilk’s test (non-preferred limb, $p = 0.287$; preferred limb, $p = 0.424$). Participants restabilized at 1114 ± 271 ms on the preferred limb as opposed to 1064 ± 257 ms on the non-preferred limb. However, there was no significant difference between the preferred and non-preferred limbs (95% CI, -54.21 to 153.66 ms), $t(28) = 0.980$, $p = 0.335$. Cohen's d effect size was calculated as 0.18.

To determine if there was a mean difference between preferred and non-preferred isokinetic peak forces normalized to body weight, a paired-samples t-test was conducted. There was no statistical difference between preferred and non-preferred limb isokinetic peak forces normalized to body weight ($p = 0.066$, Cohen's d effect size = 0.36). To assess the preferred and non-preferred limb isometric peak forces normalized to body weight, a paired-samples t-test was performed. There was no statistical difference between preferred and non-preferred limb isometric peak forces normalized to body weight, ($p = 0.194$, Cohen's d effect size = 0.25).

Pearson R Correlations

The preferred limb isometric peak force normalized to body weight and isokinetic peak force normalized to body weight were highly correlated ($r = .855$, $p < .001$). There was a non-significant negative, weak correlation for the preferred limbs time to restabilize and isokinetic peak force normalized to body weight ($r = -0.281$, $p = 0.148$) variables, as well as for the time to restabilize and isometric peak force normalized to body weight ($r = -0.171$, $p = 0.384$). For the non-preferred limb, the relationships followed a similar pattern such that there was non-significant positive, weak correlation found between the non-preferred limb isokinetic peak force normalized to body weight and time to restabilize ($r = 0.073$, $p = 0.711$) as well as no correlation between the non-preferred limb isometric peak force normalized to body weight and time to restabilize ($r = 0.152$, $p = 0.440$).

Multiple Regressions

Due to the strong correlation of preferred isometric and preferred isokinetic peak force (r > 0.7), the multicollinearity assumption was not met, therefore preferred isometric and preferred isokinetic peak force were assessed through separate regressions to improve the ability of the model to estimate each relationship independently. For the model assessing the predictability of preferred, limb time to restabilize by preferred limb isokinetic peak force normalized to body weight, age, and self-reported physical activity, linearity was found as assessed by partial regression plots and a plot of studentized residuals against the predicted values. There was independence of residuals, as assessed by a Durbin-Watson statistic of 2.306. There was homoscedasticity, as assessed by visual inspection of a plot of studentized residuals versus unstandardized predicted values. There was no evidence of multicollinearity, as assessed by tolerance values greater than 0.1. There were no studentized deleted residuals greater than ±3 standard deviations, four leverage values were greater than 0.2 (these cases were selected for removal – participants 3, 19, 23, 28), and values for Cook’s distance were all below 1. The assumption of normality was met, as assessed by a Q-Q Plot. The multiple regression model (e.g., preferred limb isokinetic peak force normalized to body weight, age, and self-reported physical activity) did not statistically significantly predict preferred limb time to restabilization, $F(3,22) = 1.274$, $p = 0.308$, $R^2 = 0.148$, and adjusted $R^2 = -0.032$ (a small effect according to Cohen (1988)).

(a) Model Summary[b]

Model	R	R Square	Adjusted R Square	St. Error of the Estimate	Durbin-Watson
1	0.385[a]	0.148	-0.032	280.23193	2.306

(b) ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	300245.878	3	100081.959	1.274	0.308[b]
	Residual	1727659.58	22	78529.936		
	Total	2027904.46	25			

(a) Model Summary; a – predictors: (constant), self-reported physical activity, age, and preferred limb isokinetic peak force normalized to body weight, b – dependent variable: preferred limb, time to restabilize
(b) Analysis of Variance (ANOVA); a – dependent variable: preferred limb, time to restabilize, b – predictors: (constant), self-reported physical activity, age, and the preferred limb, isokinetic peak force normalized to body weight

A multiple regression was also conducted to predict preferred limb time to restabilization from age, self-reported physical activity, and preferred limb isometric peak force. There was linearity as assessed by partial regression plots and a plot of studentized residuals against the predicted values. There was independence of residuals, as assessed by a Durbin-Watson statistic of 1.708. There was homoscedasticity, as assessed by visual inspection of a plot of studentized residuals versus unstandardized predicted values. There was no evidence of multicollinearity, as assessed by tolerance values greater than 0.1. There were no studentized deleted residuals greater than ±3 standard deviations, five leverage values greater than 0.2 (participants 18, 19, 28, 31, and 32) were removed, and values for Cook's distance was above 1. The assumption of normality was met, as assessed by a Q-Q Plot. The multiple regression model did not statistically significantly predict preferred limb time to restabilization, $F(3,21) = 0.779$, $p = 0.519$, $R^2 = 0.100$, and adjusted $R^2 = -0.028$ (a small effect size, according to Cohen (1988)). Age, self-reported physical activity, and preferred limb isometric peak force normalized to body weight did not statistically significantly predict time to restabilize.

(a) Model Summary[b]

Model	R	R Square	Adjusted R Square	St. Error of the Estimate	Durbin-Watson
1	0.317[a]	0.100	-0.028	282.72565	1.708

(b) ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	186906.383	3	62302.128	0.779	0.519[b]
	Residual	1678609.62	21	79933.791		
	Total	1865516.00	24			

(a) Model Summary; a – predictors: (constant), self-reported physical activity, age, and preferred limb isometric peak force normalized to body weight, b – dependent variable: preferred limb, time to restabilize
(b) Analysis of Variance (ANOVA); a – dependent variable: preferred limb, time to restabilize, b – predictors: (constant), self-reported physical activity, age, and preferred limb isometric peak force normalized to body weight

Discussion

The primary aim of this study was to determine the relationship between restabilization after foot contact in response to a forward perturbation and eccentric muscular strength in the lower limbs. We hypothesized that adults who were more efficient at restabilizing after foot contact (less time to restabilize), would produce a greater multi-joint eccentric and isometric peak force. We found that age, self-reported physical activity, and multi-joint eccentric strength (both isokinetic and isometric in individual regression models) did not statistically significantly predict restabilization time after foot contact.

It is well established throughout perturbation literature that aging is associated with decreased ability to recover from unexpected perturbations (Bosquée et al., 2021). Older adults have impairments in change-in-support reactions, lower maximal lean angle from which they can recover, often require multiple steps to restabilize, reduction of muscle mass, and altered muscle response organization, specifically more frequent co-activations of muscle mass (Mansfield et al., 2010; Carty et al., 2015; Wang et al., 2017). Based on these previous findings, it could be inferred that increased age would predict increased time to restabilize (or decreased ability to restabilize) following a forward perturbation, yet our results suggest that the multivariate model (age, self-reported physical activity, and peak force normalized to body weight) did not significantly predict time to stabilize. This could be because our participants age range (18 – 58 years of age) emphasized young to middle adulthood. In contrast, several studies focus on older adults (65 – 80) have found associations of age-related impairments in balance control (Mansfield et al., 2010; Carty et al., 2015; Wang et al., 2017).

Self-reported physical activity was not a significant predictor of time to restabilization in this study. All participants met, with many well exceeding, the recommended 500 Metabolic Equivalent of Task (MET) minutes/week minimum calculated by the Department of Health and Human Services based off the 150 minutes/week of moderate activity recommendation from the American Heart Association (*Physical Activity Guidelines for Americans, 2nd Edition*, n.d.). Therefore, the participants were fairly active which could have limited the models' ability to identify a strong correlation between self-report physical activity levels and preferred limb, time to restabilize. It is likely that, because of the younger, highly active population, the participants exceeded the minimum eccentric strength threshold for balance recovery and could contribute to these non-significant findings.

Our findings did not support our central hypothesis that greater multi-joint eccentric and isometric strength would predict decreased time to restabilize (or increased ability to restabilize) following a forward fall. Time to restabilize was poorly correlated with multi-joint eccentric and isometric peak force. Despite these findings, there are studies that suggest eccentric work is an effective strategy for recovering from forward perturbations, specifically using lower limb eccentric work to absorb falling downward momentum (Nagano et al., 2015). This may indicate an ability to absorb falling momentum by prolonging our eccentric muscle activity. If this is the case, the ability to absorb impact may have a stronger relationship to multi-joint eccentric strength and could be more indicative of balance recovery than our current variable of time to restabilize. Additionally, the hamstring and plantar flexor muscles (used largely for extension in the lower limbs) could have an important role for deaccelerating forward momentum (Saumur et al., 2020). Collectively, these studies suggest that eccentric muscular strength could have an important role in restabilization. It may have been that our fall risk variable, time to restabilize, is not the most essential component in balance recovery. For example, LaStayo et al. (2017) assessed multi-joint eccentric training and evaluated balance control through the Activities Specific Balance (ABC) Confidence Scale. The ABC self-reported scale discriminates between those who are fearful and non-fearful subjects and whether they avoid activity due to a fear of falling (Powell et al., 1995). It is possible that a self-reported scale could be more informative for balance control and whether the fear of falling influences certain activities. Or perhaps, mediolateral COP may be more informative as it has been found to be a reliable parameter in balance assessment and predictive of future fall risk (Chen et al., 2021; Carty et al., 2015).

Our findings did not support our secondary hypothesis that adults would restabilize faster on their preferred limb compared to their non-preferred limb. The mean of non-preferred limb time to restabilize was not significantly less than the mean of the preferred limb time to restabilize. A meta-analysis assessing a similar population (age 18+ years) looked to determine significant differences between dominant and non-dominant limbs in seven categories of balance performance (surface stable, eyes open; surface stable, eyes closed; surface unstable, eyes open; surface unstable, eyes closed; Balance Error Scoring System; Star Excursion Balance Test/Y Balance Test; jump) and found no significance difference between limbs for any of these variables (Schorderet et al., 2021). This supports our findings and suggests that preferred and non-preferred limb (dominant and non-dominant) typically have no difference in assessing balance recovery in young, healthy adults.

In addition to our main findings, we speculated that healthy, physically active, young to middle aged adults would be able to produce multi-joint eccentric and isometric peak forces of similar values. Our results confirmed that there were no significant differences between non-preferred and preferred limbs for both multi-joint eccentric and isometric peak forces. Similar findings in studies looking at maximal isokinetic dynamometry and asymmetries in the lower limbs found no significant differences between limb muscle strength across ages (apart from participants in their fifties in one study) (DeLang et al., 2019; Hatta et al., 2005). This suggests that our recruited population should be able to produce lower limb muscular forces that are relatively equal between both lower limbs. Moreover, we found that preferred limb, multi-joint eccentric and isometric peak forces were significantly statistically strongly, positively correlated.

Limitations

There were some limitations in this study. Our sample size was relatively small compared to some of the literature in both perturbation and eccentric muscular strength research, which could contribute to the lack of strength for prediction and correlation of our variables. It has been found that single step recovery responses are predictive of minimized fall risk and greater margin of stability in initial foot contact (Werth et al., 2021; Nagano et al., 2015). Due to the characteristics of our sample (healthy, physically active, young to middle aged adults), all participants were single steppers, which could have also contributed to the lack of strength in the correlation of our variables. Moreover, time to restabilization has been found to have low absolute reliability and it is recommended that when measuring time to restabilization to take multiple baselines (Saumur et al., 2021).

In addition, RPE is a self-reported measure and therefore runs the risk of error as participants could have not reported correctly for a multitude of reasons (e.g., misunderstanding of the scale, a mentality to not report one’s highest effort). Despite this, maximal eccentric strength testing was conducted in this study and reports of less than ten on the scale could indicate participants were not completing the test at maximal effort.

Future Research

In the future, it may be beneficial to assess rate of force development (RFD) as the primary outcome measure as well as examine the electromyography data during the phases of restabilization (e.g., take-off, swing phase, touch down, and time to restabilize). Our ability to generate muscle force quickly (e.g., RFD) and coordinate our recovery pattern has been better linked to the mechanisms of real-world falls than measures of postural sway (Carty et al., 2015). Therefore, examining how quickly one can generate eccentric muscle force may give better insight into their ability to restabilize. Additionally, it has been found during a trip that posterior muscles such as the medial gastrocnemius and biceps femoris of the stance limb are activated first as well as the plantar flexors and hamstrings of the stepping limb (Saumur et al., 2020). This indicates that eccentric muscles are responsible for preparatory lower limb muscle activation prior to foot-contact, suggesting it has an important role in AP restabilization during stepping (Singer et al., 2019). It could also be beneficial to examine co-activation of agonist and antagonist muscles via electromyography; excessive amounts of this co-activation can lead to impairments in postural responses but given in an appropriate ratio, it can modify and improve joint stability and protect from injury (Moraca et al., 2021; Pfustermeid et al., 2013).

Continuing with the current research focus, a larger sample size could be used in an older population to determine the strength of relationships between eccentric muscular strength and restabilization after a forward fall. Perhaps, conducting this protocol with older, less active (supposedly weaker) adults would yield significant findings. Older adults have been found to retain a noteworthy capability to adapt even when compared to younger adults which could be good reason coupled with the lowered perceived intensity and high metabolically efficient properties of eccentric assessment (Harper and Thompson, 2021) to explore multi-joint eccentric resistance training in combination with perturbation-based training to evaluate its impact on falls and fall prevention. Several studies have proposed perturbation-based training to improve reactive stepping for fall prevention and to predict future fall risk (Mansfield et al., 2010, Carty et al., 2015, Bosquée et al., 2021, Singer et al., 2016, Okubo et al., 2021, Werth et al., 2021). Perturbation-based training has been found to reduce the frequency of multi-step reactions, foot collisions during stepping, and time to handrail contact (Mansfield et al., 2010). It has been shown that perturbation-based training can improve reactive stepping and even has high retention capabilities (Pai et al., 2014). Specifically, the lean and release paradigm, a common form of perturbation-based training, has been found to help improve reactive stepping and determine deficiencies in reactive balance control mainly due to its task specificity (Carty et al., 2015; Bosquée et al., 2021, Werth et al., 2021). In addition, LaStayo et al. (2017) suggests that multi-joint eccentric muscle control is essential in the balance recovery process, and that multi-joint eccentric resistance training can produce significant adaptations for older adults (Harper & Thompson, 2021).

Conclusion

We conclude that age, self-reported physical activity, and multi-joint eccentric muscle strength (both isokinetic and isometric) are not significant predictors of restabilization after foot contact (time to restabilize). Multi-joint eccentric and isometric muscular strength were highly correlated as anticipated for healthy, physically active adults ages 18 – 58. There was a potential ceiling effect in this study. It is likely, due to the young to middle adult age range and their high physical activity levels, that all the participants exceeded the threshold, or absolute level of eccentric strength required to recovery from a forward perturbation. Older adults may be less likely to exceed the threshold and therefore a stronger relationship between these outcome measures could appear. Additional variables, such as RFD and electromyography, could be more essential in discovering a link between eccentric strength and balance recovery. It is important to account for the likelihood of factors other than eccentric strength playing a role in restabilization from a forward fall, such as speed of step, number of steps, and where the step is placed all involving more sensorimotor abilities. Further research is needed to examine the strength of this relationship multi-joint isokinetic muscular strength and time to restabilization in older populations as well as a thorough examination of other outcome variables (e.g., RFD and electromyography).

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