Lower Limb Muscle Weakness Predicts Use of a Multiple- Versus Single-Step Strategy to Recover From Forward Loss of Balance in Older Adults

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Background. Older adults compared with young adults have reduced strength and balance recovery ability. The purpose of the present study was to investigate whether age, sex, and/or lower limb strength predicted the stepping strategy used to recover from a forward loss of balance.

Methods. Ninety-five, community-dwelling, older adults, aged 65–90 years, participated in the study. Loss of balance was induced by releasing participants from a static forward lean. Participants performed four trials at three initial lean magnitudes and were subsequently classified as using a single- or multiple-step strategy. Isometric strength of the ankle, knee, and hip joint flexors and extensors was assessed using a dynamometer.

Results. Univariate logistic regression revealed that a unit (i.e., 1% body weight [BW] × height) decrease in ankle plantar flexion, knee extension, or hip flexion strength was associated with 1.7–2.5 times increased odds of adopting a multiple-step strategy. Women also had greater odds of requiring a multiple-step recovery strategy at the two greatest lean magnitudes. Forward stepwise logistic regression revealed that hip flexor strength in particular was influential as it was the primary predictor included in the logistic regression models at 20% and 25% BW lean magnitudes.

Conclusions. Lower limb muscle weakness, especially of the hip flexors and knee extensors, was associated with increased odds of requiring multiple steps compared with single steps to recover from forward loss of balance across a range of initial lean magnitudes. Improved balance recovery ability might be achieved by targeting these muscle groups in falls prevention programs.

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FALLS are a major cause of injury in older adults (1). Most falls occur while walking, with a forward loss of balance (e.g., a trip) being the most frequently cited mechanism (2,3). Recovery from a forward loss of balance episode requires a rapid translation of the stepping foot to a position anterior to the whole-body centre of mass (4) and the subsequent generation of recovery limb joint moments that are sufficient to counteract the forward motion of the whole body (5). An experimental paradigm for studying recovery from a forward loss of balance, which is designed to mimic a trip, involves participants being suddenly released from a static forward lean (6,7). Using this experimental approach, it has been shown that older adults have a lower maximum lean angle from which they can recover with a single step (6) and are more likely to require multiple steps to recover from a given lean angle than young adults (8,9). The tendency to use multiple steps to recover from loss of balance is also predictive of a future fall (10), and so it follows that it is important to determine the mechanisms underlying the reduced ability of older adults to recover from loss of balance with a single step.

Lower limb muscle strength decreases by 1%–4% per year from approximately 50 years of age (11–13), resulting in substantial differences in strength between young adults and persons aged in their sixties and above (14–16). Furthermore, lower limb muscle strength is lesser in women compared with men (17). Lower limb muscle weakness in older adults is also an independent predictor of a future fall (18,19). A possible explanation for this association between muscle weakness and falls is that fallers are unable to generate the required magnitude of joint moments at one or more joints during balance recovery. This suggestion is supported by findings that a systematic increase in lean...
magnitude corresponds to an increased hip flexion moment demand during the stepping phase (20), and an increased ankle, knee, and hip extension moment demand during the support phase (21) of recovery from a forward loss of balance.

Several studies have investigated the relationship between lower limb strength and the ability to recover from a forward loss of balance in older persons. Grabiner and colleagues (22) reported that lower limb, joint-specific, isometric or isokinetic strength measures accounted for no more than 30% of the variance in maximum recoverable lean magnitude among older adults, with the best predictor being maximum isokinetic dorsiflexion (DF) strength. In the study by Wojcik and colleagues (20), isokinetic hip flexion and isometric ankle plantar flexion strength were moderately correlated with the maximum recoverable lean angle in older men but not women. Arampatzis and colleagues (23) reported no differences in isometric knee extension and ankle plantar flexion strength between older adults who could recover with a single step compared with those who required multiple steps following a forward loss of balance. Given that Grabiner and colleagues (22) and Wojcik and colleagues (20) did not investigate strength in single and multiple steppers and Arampatzis and colleagues (21) focused on ankle plantar flexion and knee extension strength, it remains unclear how joint-specific strength in the lower limb is related to the strategy used to recover balance in older adults.

The purpose of the present study was to investigate whether age, sex, and/or joint-specific, isometric lower limb strength predicted the stepping strategy used to recover from a forward loss of balance (ie, single vs multiple step) following release from a range of forward lean magnitudes. It was hypothesized that age, sex, and joint-specific, isometric lower limb strength would be significant predictors of the strategy used to recover from a forward loss of balance.

**Methods**

**Participants**

Ninety-five healthy, community-dwelling older adults aged 65–90 years (51 men and 44 women; mean ± standard deviation; age, 69 ± 4 y; height, 1.67 ± 0.09 m; mass, 75.9 ± 12.4 kg) who were randomly selected from the electoral roll participated in the study. Individuals previously diagnosed with neurological, cognitive, metabolic, cardiovascular, pulmonary, or lower limb musculoskeletal impairment were excluded. All participants had normal or corrected-to-normal vision. Ethics approval was obtained from the Institutional Human Research Ethics Committee. Written informed consent was obtained from participants prior to testing and all procedures were conducted in accordance with the Declaration of Helsinki.

**Balance Recovery Task**

The balance recovery task was undertaken in accordance with Carty and colleagues (24). Participants stood barefoot with their feet shoulder-width apart in an neutral posture and were tilted forward, keeping their feet flat on the ground, until 15%, 20%, or 25% of BW was recorded on a load cell (S1W1kN, XTRAN, Australia) placed in series with an inextensible cable. One end of the cable was attached to a safety harness worn by the participant at the level of their sacrum and the other end was attached to a rigid metal frame located behind the participant. An electric winch, mounted on the frame, was used to adjust the length of the cable. Care was taken to ensure that the cable was aligned parallel with the ground and that participants kept their head, trunk, and extremities aligned prior to cable release. The cable was released at a random time interval (2–10 seconds) following achievement of the prescribed posture and cable force (±1% BW), through the disengagement of an electromagnet located in series with the cable. No differences in cable force at cable release between single steppers and multiple steppers were detected for any lean magnitudes (p > .05). Participants were instructed to relax their muscles while leaning and to regain balance with a single step using the stepping lower limb of their choice, once they perceived that they were falling. The instruction to take a single step was reiterated prior to every subsequent trial. A second cable, instrumented with a load cell (S1W1kN, XTRAN, Australia), attached the safety harness to the ceiling was used to prevent participants from contacting the ground in the event of a fall. Ground reaction forces were acquired at 1 kHz using a single piezoelectric force platform (Type 9287A, Kistler Instrument Corporation, USA) located under both feet in the prerelase position. Overhead cable force and centre of pressure location were displayed in real time on a computer monitor and were visually inspected by the investigator to ensure anticipatory actions (eg, anteroposterior and mediolateral weight shifting) were not evident in the period immediately prior to release. Following an initial practice trial at 15% BW lean magnitude, participants performed four trials at each lean magnitude, with block randomization used to determine the lean magnitude sequence (ie, 15%, 20%, or 25% BW) for the 12 trials. Trajectories of 51 reflective markers attached to the head, trunk, pelvis, and upper and lower limbs were recorded at 200 Hz using a ten-camera, three-dimensional motion capture system (Vicon Motion Systems, Oxford, UK) with whole-body three-dimensional balance recovery kinematics calculated as described previously (25).

For each lean magnitude, participants were classified as adopting a single, multiple, or mixed balance recovery strategy. The criteria used to distinguish a multiple- versus single-step strategy were (a) a second step of any kind by the stepping limb or anterior progression of the nonstepping foot past the stepping foot following its initial step (23), (b) lateral deviation of the lateral malleolus marker on the...
nonstepping foot greater than 20% of body height from its position at cable release, and/or (c) application of ≥20% of BW to the ceiling restraint cable at any point following the initial step (26). Participants who switched between use of single and multiple steps across the four trials at a given lean magnitude were classified as using a mixed strategy, and their data were excluded from subsequent analysis.

Lower Limb Strength
Maximal voluntary isometric strength of the ankle, knee, and hip flexors and extensors in the stepping lower limb, as determined from the preceding balance recovery task, was assessed using an isokinetic dynamometer (Biodex System 4, Biodex Medical Systems, USA). Ankle and knee strength were assessed in a seated position with the arms resting on the thighs. Ankle strength was assessed at 0°, 15°, and 30° of plantar flexion with the hip and knee in 90° and 60° of flexion, respectively. Knee strength was assessed at 30°, 60°, and 90°of knee flexion with the hip in 70° flexion and the ankle in 5° plantar flexion. Hip strength was assessed in a standing position at 10°, 40°, and 70°of hip flexion, with the knee constrained to a 60° flexion angle using a postsurgical knee brace. The ankle was positioned in 5° plantar flexion. A custom-made frame was used to stabilize the contralateral lower limb and the upper body during hip strength measurement. Strength measurements progressed proximally from ankle to hip and from greater flexion angles to smaller flexion angles. Submaximal practice trials were undertaken at the first angle for each joint until the investigator was confident that participants were able to produce a maximal effort. Participants performed two 3-second maximal voluntary flexion and extension trials for each joint and joint angle combination. Prior to each trial, participants were instructed to flex or extend the appropriate joint “as hard as they could” for 3 seconds, with verbal encouragement provided to maximize effort. A rest period of 60 seconds was provided between trials at each joint. Peak isometric torques at each joint were adjusted to account for the weight of the dynamometer attachment and lower limb segments distal to the joint being tested in accordance with the recommendations of Kellis and Baltzopoulos (27), using body segment parameters estimated from Dempster (28). The larger of the two peak joint torques for each angle, in each direction, were used in the subsequent analysis. Isometric strength at each joint, in each direction, was defined as the mean of the peak torques measured at each angle and was normalized to a percentage of BW (N) multiplied by height (m).

Statistical Analysis
Binary logistic regression analysis was undertaken to assess predictors of a multiple-step recovery strategy at each lean magnitude. Predictor variables were normalized joint-specific strength, age, and sex. The significance of odds ratios were assessed using the Wald test. Forward stepwise logistic regression analysis was performed for each lean magnitude using the abovementioned predictor variables. The goodness of fit of the multivariate model was assessed using the likelihood ratio test statistic (Chi-square). Statistical analyses were performed using SPSS (Version 17, SPSS, USA). Significance was accepted for \( p < .05 \).

RESULTS
The number of older adults who recovered using a single-step strategy decreased as lean magnitude increased (Figure 1). All participants who were classified as using a mixed strategy within a given condition changed from a multiple-step recovery in the initial trial/s to a single-step recovery in subsequent trials. Participants who switched stepping strategy as lean magnitude increased exhibited a change from a single- to a mixed-stepping strategy (15%–20% BW: \( n = 16 \); 20%–25% BW: \( n = 11 \)), a single- to a multiple-step strategy (15%–20% BW: \( n = 15 \); 20%–25% BW: \( n = 18 \)), a mixed- to a multiple-step strategy (15%–20% BW: \( n = 6 \); 20%–25% BW: \( n = 16 \)), or a mixed- to a single-step strategy (20%–25% BW: \( n = 1 \)).

Joint-specific, isometric muscle strengths were significant univariate predictors of a multiple-step recovery strategy (Table 1). The odds of adopting a multiple-step strategy were greater at every lean magnitude for participants with weaker ankle plantar flexors, knee extensors, or hip flexors, at the two highest lean magnitudes for participants with weaker ankle dorsiflexors or knee flexors, and at the highest lean magnitude for participants with weaker hip extensors. Women had greater odds of adopting a multiple-step strategy than men at the two highest lean magnitudes.

Forward stepwise logistic regression revealed that the only predictors of a multiple-step strategy included in the models were knee extension strength at the 15% BW condition (Chi-square = 7.78, \( p = .002 \)), hip flexion strength at the 20% BW condition (Chi-square = 14.21, \( p < .01 \)) and both hip flexion and ankle DF strength at the 25% BW condition (univariate hip flexion strength: Chi-square = 16.68, \( p < .01 \); univariate ankle DF strength: Chi-square = 8.21, \( p < .01 \); and bivariate: Chi-square = 24.89, \( p < .01 \)). All multivariate model results indicated that normalized strength was negatively associated with the odds of employing a multiple-step recovery strategy.

DISCUSSION
Our hypotheses that lower limb strength, age, and sex would predict the strategy used to recover from a forward loss of balance were partially supported by the results. Joint-specific, isometric lower limb strength did significantly predict the stepping strategy (ie, single vs multiple steps) adopted by older adults during recovery from loss of balance induced by release from a range of static forward
lean magnitudes. Univariate regression analysis performed at each lean magnitude indicated that older adults with weaker hip flexors, knee extensors, and/or ankle plantar flexors had greater odds of adopting a multiple-step recovery strategy. At the highest lean magnitude, relative weakness of hip extensors, knee flexors, and ankle dorsiflexors were also related to greater odds of taking multiple steps. Hip flexor strength in particular appears influential as it was the primary predictor included in the multivariate models at the 20% and 25% BW lean magnitudes. There was no effect of age on stepping strategy during balance recovery and while female sex was a significant univariate predictor of stepping strategy at the greater two lean magnitudes, it was not included in the final multivariate model to predict stepping strategy for any lean magnitude. In general, our findings reinforce the link between global measures of muscle weakness and balance recovery performance using a variety of balance recovery protocols (29–31), as well as global measures of muscle weakness and falls reported in a systematic review (32). A key finding of the present study is that hip flexor and knee extensor weakness, and to lesser extent, ankle plantar flexor weakness were associated with increased odds of older adults taking multiple rather than single steps to recover from forward loss of balance across a range of initial lean magnitudes.

It is difficult to make direct comparisons between the findings of the present and previous studies that have examined associations between joint-specific strength and balance recovery using the tether-release protocol because of differences in participant characteristics, protocols, outcome measures, and models of statistical analysis between studies (20,22,23). Our findings are partially aligned with those of Wojcik and colleagues (20) and Grabiner and colleagues (22), who reported evidence for statistically significant, albeit generally low to moderate, positive relationships between a range of isometric and isokinetic hip, knee, and ankle strength measures and maximum recoverable lean angle. In contrast, Arampatzis and colleagues (23) reported no differences in isometric plantar flexion or knee extension strength between older adults on the basis of their stepping strategy (ie, single vs multiple steps) when recovering from forward loss of balance from an initial lean angle of 33% BW.

Figure 1. Number and percentage of total participants employing a single-, mixed-, or multiple-step recovery strategy at each lean magnitude (BW = body weight).
The discrepancy between findings from the present study and the findings of Arampatzis and colleagues (23) may be due to differences in research design, experimental protocols, and/or participant characteristics. The present study assessed the relationships between leg strength and the recovery strategy used by older adults to recover from forward loss of balance at lean magnitudes of 15%, 20%, and 25% BW, whereas Arampatzis and colleagues (23) assessed whether leg muscle strength was different between older adults who exhibited single- or multiple-step recovery strategies to recover from forward loss of balance at a lean magnitude of 33% BW. Arampatzis and colleagues (23) used a single lean magnitude of 33% BW, which resulted in a relatively small number single steppers compared with multiple steppers (10 vs 28), whereas our study utilized a range of lean magnitudes (15%, 20%, and 25% BW), which resulted in a relatively even division of single and multiple steppers for the 20% BW condition (41 vs 37). Furthermore, the participants in the Arampatzis and colleagues (23) study were on average 5 years younger than those in the present study and thus would not have experienced the same level of age-related sensorimotor decline (33).

There was an overall trend for stronger relationships between lower limb strength measures and balance recovery strategy at the greatest lean magnitude (25% BW) than the lesser lean magnitudes (15% and 20% BW), as indicated by the goodness-of-fit statistics of the final multivariate models. In fact, muscle weakness in flexion or extension at any joint significantly increased the odds of requiring multiple steps to recover balance at the highest lean magnitude. This finding probably reflects the greater mechanical demand on lower extremity muscles when attempting to recover from more challenging lean magnitudes (21,34) and indicates a greater relative importance of lower limb muscle strength to successful recovery from a forward loss of balance of large, as opposed to intermediate and low perturbation intensities.

Women had greater odds than men of exhibiting a multiple-step recovery at the 20% and 25% BW lean magnitudes, which is consistent with previous findings that older women, in particular, have difficulty recovering from forward loss of balance with a single step (20). The lack of inclusion of female sex in the stepwise logistic regression model at any lean magnitude suggests that strength, rather than sex per se, accounted for the differences in stepping strategy employed between men and women at each lean magnitude. The absence of a significant effect of age on the odds of using a multiple- compared with single-step strategy was likely influenced by the relatively narrow age range in the study.

It is important, from a clinical perspective, to identify modifiable risk factors for falls. Our finding that lower extremity muscle strength predicts the ability to recover stability in a single step from a forward loss of balance is therefore practically significant. The hip flexors and knee extensors are predominantly responsible for forward progression of the stepping leg during balance recovery (34) and the ability to recover balance using the stepping strategy is largely influenced by the stability conditions at the end of the stepping phase (9,23). Following foot contact, the knee extensors continue to play a key role through arresting the forward and inferior momentum of the body (23). During the early stepping phase, a concentric contraction of the ankle dorsiflexors facilitates toe clearance of the stepping leg. The finding that ankle DF strength was a predictor of stepping strategy at the highest lean magnitude is consistent with the previous literature (22) and may reflect an inability of multiple steppers’ dorsiflexor muscle

### Table 1. Joint-Specific Strength, Participant Age and Sex, and the Associated Odds Ratios for Requiring Multiple Steps to Recover from Lean Magnitudes of 15%, 20%, and 25% Body Weight (bw). Odds Ratios Refer to a 1 Year Increase in Age, Female Sex, and a Unit Reduction in Normalized Strength (ie, a Percentage of bw × Height)

<table>
<thead>
<tr>
<th></th>
<th>15% BW Mean (SD)</th>
<th>15% BW Odds Ratio (95% CI)</th>
<th>20% BW Mean (SD)</th>
<th>20% BW Odds Ratio (95% CI)</th>
<th>25% BW Mean (SD)</th>
<th>25% BW Odds Ratio (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ankle DF</td>
<td>1.9 (0.5)</td>
<td>2.2 (0.8–6.4)</td>
<td>2.0 (0.6)</td>
<td>2.5 (1.0–5.9)*</td>
<td>1.9 (0.6)</td>
<td>13.4 (2.9–61.9)*</td>
</tr>
<tr>
<td>Ankle PF</td>
<td>4.5 (1.3)</td>
<td>1.9 (1.1–3.1)*</td>
<td>4.6 (1.3)</td>
<td>1.7 (1.1–2.6)*</td>
<td>4.4 (1.2)</td>
<td>2.0 (1.2–3.6)*</td>
</tr>
<tr>
<td>Knee flexion</td>
<td>3.0 (1.0)</td>
<td>1.6 (0.8–3.2)</td>
<td>3.1 (0.9)</td>
<td>1.8 (1.0–3.1)*</td>
<td>3.0 (1.0)</td>
<td>2.4 (1.3–4.5)*</td>
</tr>
<tr>
<td>Knee extension</td>
<td>6.0 (1.8)</td>
<td>1.7 (1.2–2.5)*</td>
<td>6.0 (1.7)</td>
<td>1.7 (1.2–2.4)*</td>
<td>5.9 (1.8)</td>
<td>1.9 (1.3–2.8)*</td>
</tr>
<tr>
<td>Hip flexion</td>
<td>4.1 (1.5)</td>
<td>1.8 (1.1–2.8)*</td>
<td>4.2 (1.4)</td>
<td>2.0 (1.3–3.2)*</td>
<td>4.0 (1.5)</td>
<td>2.5 (1.5–4.2)*</td>
</tr>
<tr>
<td>Hip extension</td>
<td>5.6 (1.7)</td>
<td>1.4 (0.9–2.1)</td>
<td>5.7 (1.7)</td>
<td>1.2 (0.9–1.6)</td>
<td>5.6 (1.6)</td>
<td>1.5 (1.0–2.2)*</td>
</tr>
<tr>
<td>Age</td>
<td>70 (4.0)</td>
<td>0.9 (0.8–1.0)</td>
<td>70 (4.0)</td>
<td>0.9 (0.7–1.0)</td>
<td>69 (4.0)</td>
<td>0.9 (0.7–1.1)</td>
</tr>
<tr>
<td>Sex†</td>
<td>41 F, 47 M</td>
<td>1.6 (0.5–4.8)</td>
<td>37 F, 41 M</td>
<td>2.5 (1.0–6.3)*</td>
<td>40 F, 44 M</td>
<td>14.6 (1.8–118.6)*</td>
</tr>
</tbody>
</table>

Notes: DF = dorsiflexion; PF = plantar flexion; SD = standard deviation; and CI = confidence interval.

*Significantly greater odds of requiring multiple steps, \( p < .05 \).

†Reporting number of male (M) and female (F) participants rather than a mean value.

When referring to odds ratios, the reader should note that a unit increase in strength is an absolute measure that is not adjusted for the relative strength of that muscle group compared with other muscle groups.
group to generate the joint moment required to achieve toe clearance when released from greater lean magnitudes. Our finding that lower limb muscle weakness, of the hip flexors and knee extensors in particular, was associated with exhibiting a multiple- compared with single-step balance recovery strategy therefore represents a potential target for intervention. It is well established that older sedentary persons have the ability to make considerable strength gains through participation in appropriate resistance exercise programs (35). It is therefore reasonable to suggest that strength increases of the key muscle groups identified in this study may contribute to a reduction in falls risk. Indeed Pijnappels and colleagues (31) provided preliminary evidence that strength training results in improvements in lower limb moment generation during balance recovery from a trip induced during walking.

Several factors are worthy of consideration when interpreting the findings of this study, which are as follows:

1. Multivariate odds ratios for lower limb strength were calculated using absolute measures of normalized strength (ie, they were not adjusted for the relative strength of the muscle group). This needs to be taken into account when interpreting the odds ratios and the inclusion of strength measures in the multivariate models. For example, a unit decrease in strength approximated a 50% decrease in ankle DF strength but only a 17% decrease in knee extension strength.

2. Stepping strategy is an indirect indicator of falls risk. Thus, while lower limb muscle strength was found to be negatively associated with the odds of using a multiple-step strategy to recover from a forward loss of balance, a corresponding relationship between leg strength and actual falls risk should not be inferred.

3. The strength measures employed in the study were isometric and averaged over three angles, and therefore were not specific to the joint angles and joint angular velocities achieved during the balance recovery task. For some tasks, estimates of relative effort that incorporate task-specific strength, which account for the force−length and force−velocity behavior of muscle, are superior to estimates based on maximum isometric torques (36). Although Grabiner and colleagues (22) reported relatively weak relationships between leg muscle strength and maximal balance recovery capacity, their strongest independent predictor of balance recovery capacity was an isokinetic strength measure. It is therefore possible that isokinetic strength, measured at speeds and within ranges of motion exhibited during the balance recovery task may be superior to the isometric strength measures reported here in predicting the strategy used to recover from forward loss of balance. Furthermore, while our study focused on leg strength, there is evidence that suggests that trunk muscles may also play an important role in controlling whole-body kinematics during balance recovery (9,37).

4. Finally, a degree of caution is warranted in generalizing the present findings beyond the recovery task investigated due to the specificity (eg, direction of balance loss, perturbation characteristics) of different types of falls.

CONCLUSION
Lower limb muscle weakness, especially of the hip flexors and knee extensors increased the odds of older adults requiring multiple compared with single steps to recover from a forward loss of balance across a range of initial lean magnitudes. Improved balance recovery performance might be achieved by strengthening these muscle groups in falls prevention programs targeting older persons, especially those with lower limb weakness.

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