Age and Stepping Limb Performance Differences During a Single-Step Recovery From a Forward Fall

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Background. The purpose of this study was two-fold: 1) to evaluate any age-related differences in peak joint velocities of the stepping limb during single-step recovery from a forward fall, and 2) to determine if the ability to recover from a forward fall with a single step differs when stepping with the dominant or nondominant lower limb (LL).

Methods. Ten young (19–23 years old) and ten older (65–83 years old) men were released from forward-leaning positions and attempted to recover their balance with a single step. Lean magnitude was increased until the men failed to recover their balance with a single step. The men performed the experiment twice, once while stepping with the dominant LL and once while stepping with the nondominant LL, to determine if the ability to recover from a forward fall is limb dependent. Peak joint velocities during single-step recoveries were determined.

Results. No age-related differences in peak joint velocities were found during recovery from small lean magnitudes, but older men exhibited slower velocities during recovery from maximum lean magnitudes. There was no difference in the maximum lean magnitude achieved by the men when stepping with the dominant or nondominant LL.

Conclusions. The previously reported age-related reduction in stepping speed seems to be due to localized reductions in maximum hip flexion velocity, knee flexion and extension velocity, and ankle plantar flexion velocity. Also, the ability of young and older men to recover from a forward fall with a single step does not seem to be limb dependent.

FALLS are among the most common and debilitating medical problems experienced by older adults. Approximately one-third of adults over 65 years of age fall at least once a year (1). One of the most serious injuries resulting from these falls is hip fracture. In fact, half of people over age 75 who suffer a hip fracture die within a year of the injury (2). Other potential consequences of falls besides injury include chronic pain (3), fear of falling (4), and loss of confidence (5), any of which can lead to greater functional decline in activities of daily living (6,7). The large number of falls among older adults, coupled with the expected growth in the older adult population, warns of an onerous public health problem.

Previous research has shown that the ability to recover from a fall depends largely on maximum stepping speed. For example, Wojcik and colleagues (8) reported a strong correlation between stepping speed and the ability to recover from a forward fall. Thelen and colleagues (9) suggested that the maximum stepping speed is lower in older adults than in young adults, and this lower stepping speed limits the ability of older adults to recover from falls. An age-related reduction in maximum stepping speed could potentially be caused by a localized reduction in peak joint velocity at an individual joint (i.e., hip, knee, or ankle) and/or in a specific movement direction (i.e., flexion or extension). Knowing this may allow training and rehabilitation routines aimed at fall prevention to focus on joints and/or movements most critical to fall recovery, and may improve their efficacy. Therefore, the first objective of this study was to evaluate age-related differences in peak joint velocities of the stepping limb during single-step recovery from a forward fall. Studying falls in the laboratory frequently requires the investigator to specify which foot will be used for stepping to recover from the fall (8–11). Several studies (8–12) have selected the dominant lower limb (LL) for this function, presumably by default due to lack of data to do otherwise. Muscle strength and muscle power are both thought to be important in stepping to recover from a fall, and asymmetries between the LLs have been reported in both (12–14). On the basis of these asymmetries, individuals may be better able to recover from a fall by stepping with either their dominant or nondominant LL. Knowing if the ability to recovery from a fall is not the same when stepping with the dominant or nondominant LL would allow researchers to make more informed methodological decisions when designing future fall recovery studies. Therefore, the second objective of this study was to determine if the ability to recover from a forward fall with a single step differs when stepping with the dominant or nondominant LL.

METHODS

The 20 participants included 10 young men (19–23 years old) and 10 older men (65–83 years old). Age and anthropometric characteristics of the participants are reported in Table 1. Inclusion criteria required all participants to be free of musculoskeletal injury and, for older participants, to pass a medical screening. This medical screening was performed by an internist to rule out individuals with any cardiac, respiratory, neurological, otological, or musculoskeletal disorders, or a history of repeated falls. All participants identified themselves as being right hand and right foot dominant, and reported a preference to kick a ball with their right foot. The study was approved.
by the Institutional Review Board at Virginia Polytechnic Institute and State University, and all participants signed informed consent forms prior to participation.

The protocol and experimental measures were adapted from Thelen and colleagues (9). Forward falls were induced by releasing participants from a forward-leaning position. After release, participants attempted to recover their balance using a single step of the LL specified by the investigator. Successful recoveries were followed by another trial at a larger lean magnitude. Failed recoveries were followed by a second trial at the same lean magnitude. This process was repeated until participants failed to recover their balance with a single step for two consecutive trials at the same lean magnitude. The ability to recover from a fall was quantified by the maximum lean from which participants could recover their balance with a single step after being released (LeanMAX). Participants then repeated the experiment while stepping with the opposite LL to compare LeanMAX when stepping with the dominant or nondominant LL. A crossover design was used within both age groups to balance any learning effects between participants first stepping with the dominant LL and participants first stepping with the nondominant LL.

Participants were held in the forward-leaning posture using a lean support rope. One end of the rope was attached to the back of a belt worn by the participant, and the other end was held in a releasable clasp affixed to a stable wooden structure. Participants were released by activating a solenoid that opened the clasp and released the rope. Lean magnitude was quantified by measuring tension in the rope (in percent body weight; BW) using an in-line load cell (Cooper Instruments, Warrenton, VA). Lean magnitude was adjusted by requiring participants to maintain a consistent foot position with respect to a toe line on the floor and adjusting the length of the rope.

In the event of an unsuccessful recovery, a fall to the ground was prevented using a full-torso harness tethered to a ceiling-mounted support track with a fall-prevention lanyard. The length of the lanyard was adjusted so that when the participants reached for the ground, there was approximately two inches between their fingertips and the ground. This prevented any part of the participant’s body, except the feet, from touching the ground. A load cell (Cooper Instruments) was mounted in-line with the lanyard to measure force applied to the harness.

To start each trial, participants stood with their feet shoulder-width apart at a toe line and were leaned far enough forward so that the rope behind them was taut and their body was straight except for dorsiflexion at the ankles. While in this position, participants’ heels were required to maintain contact with the ground, and participants were asked to equally distribute their weight across both feet. Equal (within 10%) weight distribution across both feet was verified post hoc during analysis. Participants were asked to keep their arms folded across their chest throughout each trial. When the participants were in position at the correct lean magnitude, they were verbally reminded which LL to use for recovery. Participants were released without warning within 10 seconds of the completion of this statement. The initial lean magnitude corresponded to 12% body weight (BW). Lean magnitude was increased by 4% BW after each successful recovery, continuing until the participant twice failed to recover his balance with a single step at a given lean magnitude. Three criteria were adapted from Thelen and colleagues (9) to define a failed recovery: 1) when more than one step was taken by the LL being tested, 2) when more than 30% BW force was applied to the harness at any point during trip recovery, and 3) when the LL opposite from the one being tested took a step longer than 30% of the participant’s body height. All participants practiced the single-step balance recovery prior to the start of the experiment.

Sagittal plane body segment positions were sampled at 200 Hz using an Optotrak optoelectronic motion analysis system (NDI, Waterloo, Ontario, Canada). Infrared markers were placed on the stepping limb side of the body at the fifth metatarsal head, heel, lateral malleolus, lateral femoral epicondyle, greater trochanter, and acromion. Marker data were filtered with a fourth order, 7 Hz low-pass, zero-phase-shift Butterworth filter. In the initial forward-leaning position, a forceplate was under each foot (AMTI, Watertown, MA). Forceplate and harness load cell data were sampled at 1000 Hz, and load cell data were subsequently filtered with a fourth order, 10 Hz low-pass, zero-phase-shift Butterworth filter. Six measures of stepping limb kinematics were calculated from the marker data, including peak joint velocities in flexion and extension at the hip, knee, and ankle. These measures were calculated for the time interval between release to the instant that the stepping LL contacted the floor; only trials in which participants successfully recovered their balance while stepping with their dominant (right) LL were included in the joint velocity analysis. Two LeanMAX values for each participant were determined: one while participants stepped with the dominant LL, and one while they stepped with the nondominant LL. Lean magnitude (units of % BW in the lean support rope) was converted to lean angle (units of degrees) using the method reported by Thelen and colleagues (9). All experiments were recorded on videotape for post hoc confirmation of fall recovery and/or failure criteria.

To determine if peak joint velocities vary with lean magnitude and age, a multiple regression analysis was used. The regression equation had the following form:

$$\text{Peak joint velocity} = b_0 + b_1 (\text{lean}) + b_2 (\text{lean}^2) + b_3 (\text{AGE}) + b_4 (\text{AGE} * \text{lean})$$

where AGE was a dummy variable equal to 0 for young participants and 1 for older participants. The (lean$^2$) term was included to accommodate potential nonlinearities in the relationship between peak joint velocity and lean magnitude, and the (AGE * lean) term was included to accommodate a potential interaction between age and lean.

### Table 1. Subject Anthropometric Data

<table>
<thead>
<tr>
<th></th>
<th>Young</th>
<th>Older</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>20.6 (1.3)</td>
<td>74.0 (6.5)</td>
</tr>
<tr>
<td>Height, cm</td>
<td>176.0 (6.8)</td>
<td>171.4 (5.8)</td>
</tr>
<tr>
<td>Mass, kg</td>
<td>71.3 (14.0)</td>
<td>77.0 (14.0)</td>
</tr>
</tbody>
</table>

Note: Values are mean (standard deviation).
magnitude. Regression coefficients significantly different from zero (p < .05) indicated which independent variables made a significant contribution to the prediction of peak joint velocity. For example, a significant $b_3$ term indicated a significant age effect on peak joint velocity while holding lean magnitude constant. Within each age group, only leans with at least two participants were included in the regression analysis to prevent any single participant from having a disproportionately large influence on the analysis. Independent $t$ tests were used to determine if peak joint velocities used during recovery from LeanMAX differed between age groups. To determine if the ability to recover from a forward fall with a single step differed when stepping with the dominant or nondominant LL, a two-way repeated measures analysis of variance (ANOVA) was used with age and stepping LL as the independent measures, and LeanMAX was used as the dependent measure. A significance level of 0.05 was used, and all statistical analyses were conducted using SPSS V11.5 (SPSS, Inc., Chicago, IL).

**RESULTS**

**Age and Stepping Limb Differences in LeanMAX**

Young participants achieved a larger LeanMAX than did older participants [33.4 ± 5.4% BW (mean ± standard deviation) versus 20.7 ± 6.2% BW; p < .001]. Equivalent lean angles (measured in degrees) corresponding to these lean magnitudes (Table 2) were 28.8 ± 4.2° for young participants, and 20.2 ± 4.1° for older participants. No difference in LeanMAX was found between dominant and nondominant LL (27.6 ± 9.4% BW vs 27.2 ± 8.0% BW; p = .812, Figure 1); this result was consistent for both age groups because the Age × Stepping Limb interaction term was not significant (p = .245). In addition, the primary reason for failure at magnitudes beyond LeanMAX was similar for both LL (harness failure for young participants, and multiple steps for older participants). One older participant could not recover his balance after being released from the minimum lean magnitude with either LL, and therefore could not be included in the analysis. All other participants completed at least the minimum lean magnitude for both LLs.

**Peak Joint Velocities of Stepping Limb**

Sample joint velocities during a typical recovery are shown in Figure 2. General observations of the data indicate that peak joint velocities during single-step recoveries were highest at the knee (in both flexion and extension), followed by hip flexion and ankle plantar flexion (Figures 3 and 4). Peak joint velocities in ankle dorsiflexion and hip extension were similar. This general trend was consistent across both age groups. Peak joint velocities exhibited a significant increase as lean magnitude increased, with the exception of peak ankle dorsiflexion velocity and peak hip extension velocity. No AGE coefficients in the multiple regression equations were significant, indicating that there were no age-related differences in peak joint velocities between age groups while holding lean magnitude constant. However, age-related differences were found during recovery from

**Table 2. Conversion Between Percent Body Weight in Lean-Support Rope and Mean Equivalent Lean Angles**

<table>
<thead>
<tr>
<th>Rope Tension (% Body Weight)</th>
<th>Lean Angle (Degrees)</th>
<th>Young</th>
<th>Older</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>11.8</td>
<td>11.8</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>14.8</td>
<td>16.1</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>18.1</td>
<td>19.6</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>21.4</td>
<td>21.3</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>24.3</td>
<td>22.7</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>27.1</td>
<td>26.6</td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>30.5</td>
<td>30.0</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>33.9</td>
<td>37.1</td>
<td></td>
</tr>
<tr>
<td>44</td>
<td>37.1</td>
<td></td>
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</tbody>
</table>

Figure 1. Maximum lean magnitude (LeanMAX) when stepping with the dominant and nondominant lower limb. Error bars indicate standard deviations. Results showed a significant age effect on LeanMAX, no effect of lower limb on LeanMAX, and no interaction. BW = body weight.

Figure 2. Sample joint velocities during a single-step recovery after a young participant was released from a lean magnitude of 28% BW (25° lean angle). Positive values indicate hip flexion, knee flexion, and ankle dorsiflexion. BW = body weight.
physical demands (Figures 3 and 4). However, peak joint velocity related to muscle contraction performance include age-related reductions in muscle strength [see (15) for a review] or torque development rates (16). These reductions may limit joint torques, and the resulting joint motion, during the short time available to perform a recovery step. Another potential cause is an age-related difference in muscle activation pattern to compensate for changes in muscle contraction performance with age. Thelen and colleagues (17) reported delayed deactivation of the rectus femoris muscle (a hip flexor and knee extensor) in the stepping limb during single-step recovery from a forward fall. This delay

LeanMAX. Older men exhibited slower peak hip flexion velocity (p < .001), peak knee flexion velocity (p < .001), peak knee extension velocity (p = .002), and peak ankle plantar flexor velocity (p = .007) (Table 3). No age-related differences were found in peak ankle dorsiflexion velocity and peak hip extension velocity during recovery from LeanMAX.

DISCUSSION

The first objective of this study was to evaluate age-related differences in peak joint velocities of the stepping limb during single-step recovery from a forward fall. Both young and older participants used similar peak joint velocities during balance recoveries at lean magnitudes ≤ 24% BW, i.e., balance recoveries requiring lower physical demands (Figures 3 and 4). However, peak joint velocities during recovery from the largest achieved lean magnitudes did show age-related differences. Specifically, older participants exhibited 27% smaller peak hip flexion velocity, 30% smaller peak knee flexion velocity, 25% smaller peak knee extension velocity, and 28% smaller peak ankle plantar flexion velocity compared to young participants (Table 3). These differences imply that the maximum speed at which older men can flex their hips, flex their knees, extend their knees, and plantarflex their ankles is significantly lower than that in young men. Furthermore, these lower velocities may be causally related to the smaller LeanMAX in the older participants. These results also suggest that age-related differences in fall recovery mechanics may only be apparent during recoveries requiring high physical demands, a similar conclusion to that made by Thelen and colleagues (9).

Peak ankle dorsiflexion velocity and peak hip extension velocity did not increase with lean magnitude (Figures 3 and 4), suggesting that increasing these velocities is not critical during physically demanding fall recoveries. Peak ankle dorsiflexion velocity and peak hip extension velocity at LeanMAX did not differ between age groups (Table 3), suggesting that older participants' reduced ability to recover from a fall with a single step was not caused by insufficient velocities in these directions. Together, these results suggest that increases in some peak velocities (hip flexion, knee flexion, knee extension, and ankle plantar flexion) have a greater effect than others (hip extension and ankle dorsiflexion) on the ability to recover balance with a single step. These results indicate that emphasizing training and/or rehabilitation protocols for fall prevention on improving peak joint velocities in hip flexion, knee flexion, knee extension, and ankle plantar flexion may prove beneficial.

There are several potential causes of these age-related differences in peak joint velocities. Two potential causes related to muscle contraction performance include age-related reductions in muscle strength [see (15) for a review] or torque development rates (16). These reductions may limit joint torques, and the resulting joint motion, during the short time available to perform a recovery step. Another potential cause is an age-related difference in muscle activation pattern to compensate for changes in muscle contraction performance with age. Thelen and colleagues (17) reported delayed deactivation of the rectus femoris muscle (a hip flexor and knee extensor) in the stepping limb during single-step recovery from a forward fall. This delay was

Table 3. Peak Joint Velocities at Maximum Leans

<table>
<thead>
<tr>
<th>Joint and Direction</th>
<th>Young</th>
<th>Older</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak hip flexion velocity, degrees/s</td>
<td>475.2 (72.0)</td>
<td>348.7 (53.3)*</td>
</tr>
<tr>
<td>Peak hip extension velocity, degrees/s</td>
<td>104.6 (51.9)</td>
<td>106.6 (37.3)</td>
</tr>
<tr>
<td>Peak knee flexion velocity, degrees/s</td>
<td>698.3 (43.9)</td>
<td>488.0 (99.7)*</td>
</tr>
<tr>
<td>Peak knee extension velocity, degrees/s</td>
<td>713.5 (80.0)</td>
<td>534.9 (134.0)*</td>
</tr>
<tr>
<td>Peak ankle dorsiflexion velocity, degrees/s</td>
<td>96.6 (48.0)</td>
<td>107.1 (33.4)</td>
</tr>
<tr>
<td>Peak ankle plantarflexion velocity, degrees/s</td>
<td>354.4 (56.4)</td>
<td>256.0 (35.7)*</td>
</tr>
</tbody>
</table>

Notes: Values are means (standard deviation). These values were calculated for trials in which participants successfully recovered by stepping with their right leg.

*p < .001 for age effects.

*p = .002 for age effects.
may reflect an attempt to boost hip flexion velocity and/or knee extension velocity but may have the negative consequence of decreasing knee flexion velocity.

The second objective of this study was to determine if the ability to recover from a forward fall with a single step differs when stepping with the dominant or nondominant LL. Pavol and colleagues (18) found that obstructing the dominant or nondominant foot to induce a trip resulted in almost identical percentages of successful and failed trip recoveries. However, the foot used for recovery was not controlled in this study in an effort to maintain "natural" reactions (18). As such, the results of Pavol and colleagues do not necessarily indicate if fall recovery capability is equal when stepping with the dominant or nondominant LL. Our findings indicate that the ability to recover from a forward fall with a single step is not limb dependent for both young and older men.

Several limitations of the current study warrant discussion. Unlike many falls outside of the laboratory, our participants were expecting a fall during the experimental protocol. We feel, however, that our results are mostly a function of participant physical performance capabilities, which would not be expected to differ whether falls were induced expectedly or unexpectedly. The age-related differences in peak joint velocities documented here, if causally related to the smaller LeanMAX of older participants, are unlikely to be the only motor-related factors that caused smaller LeanMAX in older participants. Other motor-related factors that have been suggested include joint kinetics in the stepping limb after stepping, and in the nonstepping limb (19). Lastly, our study included only male participants to avoid potential sex effects. As a result, the results may not apply to women.

Conclusion

Older men exhibited a decreased ability to recover from a fall with a single step compared to young men, and this decreased ability may be due to an age-related reduction in peak hip flexion velocity, knee flexion velocity, and ankle plantar flexion velocity. In addition, the ability of young and older men to recover from a forward fall with a single step does not seem to be dependent on the LL used for stepping.

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REFERENCES


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