Age Influences the Outcome of a Slipping Perturbation During Initial But Not Repeated Exposures

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Background. Fall incidence in older adults might be reduced through learning to better recover from or adjust to perturbations. Extents of age-related declines and limitations in the ability to recover are not well established, however.

Methods. Slips were induced, using bilateral low-friction platforms, during a sit-to-stand task in 60 young and 41 older, healthy, safety-harnessed adults. Subjects underwent five slips, a block of nonslipping trials, then two reexposures to the slip. The first slip was novel and unexpected. Age-group and trial effects on fall incidence (evidenced by excessive hip descent) and on the direction of the initial protective step were examined.

Results. More older than young adults fell upon the first slip (73% vs 28%; p < .001). With repeated exposure, fall incidence decreased at similar exponential rates in both age groups. All but one subject eventually learned to slip without falling, and two-thirds of fallers fell only once. Repeat fallers fell without stepping in 63% of falls. Upon later slip reexposure, more older than young adults fell (20% vs 2%), but fewer falls occurred than did originally (p = .001). Likelihoods of forward and backward stepping during successful recovery changed with repeated slip exposure and upon reexposure, but did not differ between age groups.

Conclusions. Older adults are more likely to fall upon initial, unexpected perturbation exposure, but, upon repeated exposure, healthy young and older adults rapidly learn to avoid falling at a similar rate. Healthy older adults appear fully capable of learning to better recover from or adjust to a perturbation through repeated exposure.

Falls are a significant cause of activity restriction, functional decline, serious injury, and even death in older adults (1–3). Effective means of preventing falls by older adults are therefore needed. Fall prevention efforts to date have focused primarily on identifying those at risk (4,5), implementing exercise interventions to improve strength, balance, flexibility, and/or fitness (6,7), and reducing environmental hazards (8,9). Yet, these do not directly address the presumed common factor in all falls: a failure to recover following a loss of balance.

The extent to which age-related declines exist in the ability to actively recover from an unexpected perturbation is not well established. Although numerous age-related deficits in postural control and performance have been demonstrated (10), almost all evidence relates to unpredictable but expected perturbations that did not lead to falls. Among these findings, older adults sway more when perturbed (11,12), may step in response to smaller perturbations (13,14), may take more steps during recovery (15), and must initiate stepping from lesser body inclinations to recover with a single step (16). If deficits can also be demonstrated in the ability to avoid a fall through the unconstrained responses to a large, unexpected perturbation, these deteriorated responses would present a target for intervention.

Fall incidence might potentially be reduced by training older adults to better recover from or adjust to perturbations. Adaptations consistent with an increased ability to recover from a specific perturbation have been observed in the recovery responses of healthy young (17–20) and older adults (11,21) upon repeated exposure to a perturbation. However, to our knowledge, only one study has directly shown that healthy older adults who fall can learn to recover from a specific, expected perturbation through repeated exposure (22). Because this ability to learn to avoid falling has been studied for only one type of perturbation, a backward support surface acceleration during quiet standing, the general applicability of these findings is unknown.

Furthermore, while healthy older adults are capable of motor learning, age-related limitations to this ability have not been widely explored. Young and older adults learn similarly from prior outcomes (23,24). Nevertheless, older adults typically exhibit poorer performance during and after motor learning (24,25) and may be unable to adapt to some tasks (11) due to age-related functional declines. For purposes of fall prevention, the extent to which older adults may be limited in their ability to learn to recover should be established. Also, given the oft-observed differences in motor behavior between young and older adults (26–29), it should be determined whether older adults, by choice or necessity, adjust differently to a perturbation.

This study addressed these issues using a novel type of perturbation in which a slip is induced during a sit-to-stand movement (30). The study investigated whether young and
older adults would differ in fall incidence upon initial, unexpected perturbation exposure, differ in the rate of decrease in falls upon repeated exposure, and differ in fall incidence upon later reexposure. Relationships between increased falling and the likelihood of stepping were considered. Finally, the study investigated whether adjustment to the perturbation, as indicated by the likelihoods of stepping associated with recovery, would vary as functions of age group and exposure history.

**Methods**

**Subjects**

Forty-one healthy older adults (21 women) and 60 healthy young adults (44 women) gave written informed consent and were paid to participate. Institutional Review Board approval was obtained. Older adults were ambulatory, community-dwelling individuals (mean ± SD age: 73 ± 5 years [range: 65–85]; height: 1.69 ± 0.09 m; mass: 79 ± 14 kg). Young adults were generally students (age: 25 ± 5 years [range: 18–41]; height: 1.69 ± 0.10 m; mass: 67 ± 14 kg). Subjects were screened for self-reported exclusionary factors that included neurological, musculoskeletal, cardiopulmonary, and other systemic disorders and selected drug usage (e.g., tranquilizers). Older adults were tested to screen for cognitive impairment, poor mobility, and orthostatic hypotension. Calcaneal bone mineral density was assessed by ultrasound (Hologic Sahara, Bedford, MA), and older adults classified as osteopenic or osteoporotic (i.e., T-score < −1) were excluded.

**Experimental Protocol**

Slips were induced during a sit-to-stand movement using a side-by-side pair of low-friction platforms (dimensions: 31 × 29 × 2.5 cm; friction coefficient: 0.02; Figure 1). These were free to slide 24 cm forward upon release of their locking mechanisms. Platforms slid independently and latched into place in their maximum forward positions. Although subjects could slide the platforms relative to each other during a slip, at least one platform traveled the maximum distance in 99.5% of cases. Subjects wore a full-body safety harness, attached at the shoulders to a ceiling-mounted support by a pair of shock-absorbing dynamic ropes, typically used for fall protection in rock climbing. Rope lengths were adjusted so the knees could not touch the flooring. A load cell measured the force exerted on the ropes.

Trials began with subjects sitting on a stool in a standardized position. One shoe rested on each platform with its heel at the rear edge and the feet a self-selected width apart. Ankles were dorsiflexed 10°, knees were flexed 80°, and arms were at the sides with the elbows flexed 90°. Subjects were informed that they would initially be performing sit-to-stand trials and that “later on” a slip would take place. No practice was given, and the exact trial, timing, or mechanisms of the slip were not provided. Upon an auditory cue, subjects were to stand up “as quickly as possible,” without using their arms, then remain standing still. After four normal sit-to-stand trials, a slip was induced without warning.

A computer controlled the timing of the slip, simultaneously releasing both platforms when the stool supported less than 10% body weight and the forward velocity of the body center of mass exceeded 20 cm/s. The slip was thereby initiated early in the braking phase after seat-off. Platform release data were computed in real time from three force plates (AMTI, Newton, MA) located beneath the stool and each platform, respectively, with center of mass velocity computed from the integral of the measured shear forces.

Following the first slip, subjects were informed that a slip “may or may not occur” during subsequent trials. It was emphasized that they should “try not to fall,” then remain standing still afterward. The remaining instructions were as before. No additional information was provided. Subjects underwent a block of five consecutive slipping trials. This was followed by a nonslipping block of at least three consecutive unperturbed trials; a fourth or fifth trial was added if stepping occurred during the preceding trial. Subjects were then reexposed to two slipping trials. All trials were at least 1 minute apart.

The kinematics of 26 markers attached to the bilateral upper and lower extremities, torso, and platforms were recorded by a motion capture system at 60 Hz (Peak Performance, Englewood, CO). Marker paths were low-pass...
filtered at marker-specific cut-off frequencies (range: 4.5–9 Hz) using recursive, fourth-order Butterworth filters. Force plate and safety harness data were collected at 600 Hz.

**Data Analysis**

Trial outcomes were classified as **falls** if the midpoint of the bilateral hip markers descended within 5% body height of its initial seated height. Qualitatively, all falls were backward. Most often (n = 56), the body descended in front of the stool in an approximate stand-to-sit motion, with varying degrees of hip and knee flexion and little or no step exhibited (Figure 2). In seven falls, the stepping limb collapsed beneath the hips. The remaining falls (n = 15) exhibited progressive hip descent over multiple backward steps. Other outcomes were classified as **recoveries** if the average force on the safety harness did not exceed 4.5% body weight over any 1-second period. The remaining outcomes were considered harness-affected and were visually classified into two subgroups. **Affected recoveries** corresponded to forward balance losses from an erect standing posture and almost certainly would not have resulted in falls, even if the harness were absent; harness forces arose from trunk flexion or a large forward step after attempts to remain standing without stepping (Figure 2). In the remaining, **affected falls**, a fall more likely would have occurred; in most cases, subjects grabbed the harness or stepped to regain balance but did not arrest their backward motion. Finally, those with more than one fall within the first block of slipping trials were considered **repeat fallers**. Outcome classification thresholds were determined post hoc from visible divisions in the data distributions and were confirmed by video data.

Harness effects were defined to start when the average safety harness force first exceeded 4.5% body weight over the preceding 1-second period. The **time of fall** was defined as the earlier of (i) the start of harness effects or (ii) 66 ms before the end of the first descent of the bilateral hip midpoint below the fall criterion. The latter assumes that harness-induced decelerations began at the average time whereby the start of harness effects preceded the end of descent across all observed falls.

Where stepping occurred, the direction of the initial step was determined. Times of step lift-off and touchdown were identified from the vertical forces recorded by the force plates or, if touchdown occurred outside the force plates, from foot kinematic data. Step direction (forward or backward) was determined by the change in the sagittal displacement of the ankle marker of the stepping foot with respect to that of the nonstepping foot between lift-off and touchdown. When lift-off occurred after the time of fall, the step was excluded.

**Statistics**

Age-group and between-trial differences in the likelihood of falling were tested for the first slip and the first reexposure after the nonslipping block using a multivariable logistic regression analysis that considered interaction and clustering (i.e., repeated measures) effects. An age difference in the rate at which the percentage of subjects who fell declined over the first block of slipping trials was tested by determining whether $K_2$ differed from zero in the nonlinear regression model:

$$
(\% \text{ falls}) = (C_1 + C_2 \cdot \text{age})e^{(K_1 + K_2 \cdot \text{age})(\text{trial}−1)}
$$

where age equals 0 for young and 1 for older adults.

Using Fisher’s exact test, the proportions of falls without stepping were compared between age groups for the first slip and between one-time fallers and repeat fallers across all falls in the first block of slipping trials. Age-group and between-trial differences in the likelihoods of using an initial forward step, backward step, or no step to successfully recover were tested across the second through fifth slipping trials using a multivariable, multinomial logistic regression analysis. The same differences in step likelihood were tested, with respect to the first and fifth slipping trials, for the first slip reexposure after the nonslipping block using a pair of multivariable, multinomial logistic regressions with a Bonferroni correction. Recovery without stepping was the reference category for all multinomial regressions, and both interaction and clustering effects were considered.
Occasionally, due to equipment malfunction or experimenter error, data were lost, or a slip did not occur as intended. Such trials were excluded from analysis, as were subsequent trials within the same block. Data for seven young adults were excluded due to persistent problems. Harness-affected trials were also excluded from analysis due to uncertainty regarding the true outcome absent the harness. Analyses were performed using STATA 7.0 (Stata Corp., College Station, TX) or SPSS 10.0 (SPSS, Inc., Chicago, IL). A significance level of .05 was used throughout.

**Results**

Older adults were more likely than young adults to fall upon the first, novel and unexpected slip \((p < .001; \text{Figure 3})\). While only 28% of young adults fell upon the first slip, 73% of older adults fell. Older adults also tended to be more likely to fall without stepping (Table 1). Among those who fell, 33% of older adults did not step upon the first slip, as compared to 13% of young adults \((p = .28)\). All subjects admitted to being surprised by the first slip.

Fall incidence decreased exponentially with repeated exposure to the slip, and the rate of decrease did not differ \((p > .05)\) between young and older adults (Figure 4). Except for one older adult, all subjects eventually learned to slip without falling and, once successful, did not fall again during the first block of slipping trials. Two thirds of subjects who fell, both young and older, did so only once, when the slip was novel and unexpected. However, one young

![Figure 3. The distribution of outcomes in each trial for (A) young and (B) older adults. The percentage of subjects with each outcome is shown for the slip and unperturbed (nonslip) trials. Falls correspond to a descent of the hips to near-seated height. Recovery was associated with negligible force on the safety harness. All other outcomes were considered harness-affected. Based on visual inspection, affected recoveries and affected falls would likely have resulted in recoveries and falls, respectively, were the harness absent. Trials were performed in left-to-right order.](#)

### Table 1. Influence of Age, Trial, and Outcome on the Incidence and Direction of the Initial Protective Step

<table>
<thead>
<tr>
<th>Age Group and Outcome</th>
<th>Step Direction</th>
<th>Preslip Trial</th>
<th>Slip Trials</th>
<th>Nonslip Trials</th>
<th>Slip Trials</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1 2 3 4 5</td>
<td>1 2 3 4 5</td>
<td>1 2</td>
<td>1 2</td>
</tr>
<tr>
<td><strong>Young Adults</strong> ((n = 53))</td>
<td>Recover Back</td>
<td>— 31 19 6 3 2</td>
<td>— 1 — — —</td>
<td>25 7</td>
<td>— — — — —</td>
</tr>
<tr>
<td></td>
<td>None 53</td>
<td>— 14 17 25 30</td>
<td>— 2 31 49 23</td>
<td>42 — — — —</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Forward —</td>
<td>— 10 17 16 14</td>
<td>46 18 4 1 2</td>
<td>— — — — —</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fall Back —</td>
<td>— 13 — — — —</td>
<td>— — — — —</td>
<td>— — — — —</td>
<td></td>
</tr>
<tr>
<td></td>
<td>None — 2 5 1 1</td>
<td>— — — — — —</td>
<td>— — — — —</td>
<td>— — — — —</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Forward —</td>
<td>— — — — — —</td>
<td>— — — — —</td>
<td>— — — — —</td>
<td></td>
</tr>
<tr>
<td><strong>Older Adults</strong> ((n = 41))</td>
<td>Recover Back</td>
<td>— 9 22 10 6 5</td>
<td>— 5 37 41 8 24</td>
<td>— 23 11</td>
<td></td>
</tr>
<tr>
<td></td>
<td>None 41</td>
<td>— 6 15 24 23</td>
<td>— 5 37 41 8 24</td>
<td>— 23 11</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Forward —</td>
<td>— 3 11 8 10</td>
<td>— 35 4 1 3</td>
<td>— — — — —</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fall Back —</td>
<td>— 19 4 1 1 1</td>
<td>— — — — —</td>
<td>— — — — —</td>
<td></td>
</tr>
<tr>
<td></td>
<td>None — 10 6 2 1</td>
<td>— — — — —</td>
<td>— — — — —</td>
<td>— — — — —</td>
<td></td>
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<td></td>
<td>Forward —</td>
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</tbody>
</table>

*Notes: The number of subjects exhibiting each behavior are shown for the slip and unperturbed (preslip and nonslip) trials. Trials were performed in left-to-right order. Data for harness-affected and excluded trials are not shown.*
and four older adults fell three or more times. Repeated falling was associated with a lack of stepping. Across age groups, 63% of 38 falls by the 15 repeat fallers in the first block of slipping trials exhibited no stepping, versus 13% of 30 falls by one-time fallers ($p < .001$).

The likelihood of using an initial forward or backward step to successfully recover changed with repeated exposure to the slip (Figure 5) but did not differ between young and older adults ($p = .18$; Table 1). All but one recovery upon the first slip included a backward step. Thereafter, from the second to the fifth slipping trial, the odds of using a backward step for recovery (vs recovery without stepping) decreased by a factor of 2.7 per trial ($p < .001$) while the corresponding odds of using a forward step for recovery remained constant ($p = .39$). Interactions between age group and trial were not significant ($p = .14$).

No subject fell when, after repeated exposure and without warning, the slip did not occur. However, 88% of subjects stepped forward during a task that originally required no steps (Table 1). Subjects quickly adjusted for the absence of the perturbation; by the third trial of the nonslipping block, only 4% of subjects stepped.

Upon reexposure to the slip without warning after the nonslipping block, the odds of falling were 24.0 times lower than for the first slip ($p = .001$), regardless of age group ($p = .59$ for the age-by-trial interaction; Figure 3). Older adults thus remained more likely than young adults to fall ($p < .001$). All eight older adults who fell upon reexposure to the slip also fell upon their first slip, with six of these subjects among the repeat fallers of the first block. The young adult who fell upon reexposure also fell upon her first two slips. Apart from one older adult who never slipped without falling, subjects who fell upon reexposure to the slip immediately readjusted for it; none fell during a second reexposure (Figure 3).

Upon first reexposure to the slip, the likelihood of using an initial forward or backward step to successfully recover differed from both the first and fifth slips of the earlier slipping block (Figure 5), but did not differ between young and older adults ($p > .068$; Table 1). Use of a backward step (vs no step) for recovery was less likely upon reexposure than upon the first slip ($p = .002$). Conversely, backward steps were more likely ($p < .002$), and forward steps were less likely ($p = .022$) upon reexposure than upon the fifth slip.

**DISCUSSION**

The outcomes of the first slip confirmed that healthy older adults are at greater risk than young adults of falling from a perturbation that is novel and unexpected. Furthermore, because all subjects were exposed to the same perturbation, the increased falling by older adults reflected a decreased ability to actively recover from the impending fall. While it is generally believed that older adults are less able to recover, most experimental evidence (10) relates to the ability to maintain balance without stepping (11–14), the ability to execute a prescribed stepping task (16), or the use of multiple steps to regain balance (15). The present results provide direct evidence of an age-related decline in the ability to recover based on self-selected recovery responses leading to actual “falls.”

Falling was related to the specific execution of the sit-to-stand task and/or the response to the slip, not to insufficient functional capacity, as all but one subject learned to slip without falling. In fact, most subjects who fell, both older and young, did so only when the slip was novel and unex-
INFLUENCES OF AGE ON SLIP OUTCOME

Table 2. Influence of Age and Trial on the Number of Steps Used During Successful Recovery

<table>
<thead>
<tr>
<th>Age Group and No. of Steps</th>
<th>Preslip Trial</th>
<th>Slip Trials</th>
<th>Nonslip Trials</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td><strong>Young Adults (n = 53)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 Steps</td>
<td>53</td>
<td>1</td>
<td>14</td>
</tr>
<tr>
<td>1 Step</td>
<td>3</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>2 or More Steps</td>
<td>28</td>
<td>20</td>
<td>13</td>
</tr>
<tr>
<td><strong>Older Adults (n = 41)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 Steps</td>
<td>41</td>
<td>—</td>
<td>6</td>
</tr>
<tr>
<td>1 Step</td>
<td>—</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>2 or More Steps</td>
<td>9</td>
<td>20</td>
<td>12</td>
</tr>
</tbody>
</table>

Notes: The number of subjects who recovered and exhibited each behavior are shown for the slip and unperturbed (preslip and nonslip) trials. Trials were performed in left-to-right order.
ping conditions (i.e., the last trial of the nonslipping block and the first slip reexposure).

It should be considered that the present results are based on a population of healthy, community-dwelling older adults, only one of whom reported a history of falling. Lesser effects of repeated exposure on falling might be observed in frailler populations with impaired mobility or cognition. Furthermore, insufficient functional capacity might limit the perturbation magnitudes from which frail older adults could learn to recover. Nevertheless, we expect that, for perturbations within these limits, even frail older adults would learn upon repeated exposure.

Other limitations relate to the safety harness. The harness-affected outcomes unavoidably introduced ambiguity into the results. This was of little effect, however. Had affected recoveries been recovered and affected falls been falls, the results of all statistical analyses associated with fall incidence would have been unchanged. Of greater possible effect were the indeterminable and variable influences of the safety harness on behavior. In extreme cases, subjects grabbed the harness. However, a few, mostly young, subjects also appear to have chosen to fall into the harness rather than step. With no clear basis for differentiating voluntary from involuntary falls, our results unavoidably include both. Outcomes could also have been affected by between-subject variations in preparedness and task perception, despite our having provided the same instructions and information.

One must be careful in interpreting the present results. This study investigated the ability to learn to slip without falling upon repeated exposure to a single perturbation during a single task within a single experimental session. The extent to which such learning would transfer to recovery from unexpected perturbations of different types, magnitudes, and directions during different activities of daily living is unknown. The extent to which the observed learning persisted beyond the experimental session is also unknown. These important issues must be addressed before the potential effectiveness of training older adults to better recover from or adjust to perturbations can be established for fall prevention. Nevertheless, the fact that older adults were able to learn within the limitations of the present protocol is encouraging.

This study found that older adults are more likely than young adults to fall upon initial, unexpected exposure to a perturbation but that, upon repeated perturbation exposure, healthy young and older adults can and will learn to avoid falling at a similar, exponential rate. Effects of such learning can also persist upon later perturbation reexposure. Those with poor abilities to appropriately adjust for or react to a perturbation appear to be at high risk of repeated falling. Our results suggest that through repeated perturbation exposure, potentially in a clinical setting, older adults might develop and maintain the ability to adjust for and react to a perturbation, thereby reducing their likelihood of falling.

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