Young and Older Adults Exhibit Proactive and Reactive Adaptations to Repeated Slip Exposure

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Background. A previous study found that, with repeated exposure to slipping during a sit-to-stand task, fall incidence decreased at a similar exponential rate in young and older adults. This study investigated the adaptations responsible for this decrease.

Methods. Slips were induced, using bilateral low-friction platforms, during a sit-to-stand in 60 young and 41 older healthy safety-harnessed adults. Participants underwent 5 slips, then a 6th slip (reslip) after 3–4 nonslipping trials. Between-trial adjustments in body center of mass state at seat-off were examined and correlated to the likelihoods of falling and stepping. Changes in reactive response between the first slip and reslip were investigated.

Results. With repeated slipping, both young and older adults adjusted to increase their center of mass anterior position and forward velocity at seat-off (p < .001), contributing to decreased fall incidence and changes in step incidence and direction (p < .001). These proactive adjustments predicted fall incidence well in later trials, but underpredicted fall incidence upon the first slip by 9%–21%, suggesting that reactive response deficiencies also initially contributed to falls by both age groups. Ten participants who initially fell without stepping adapted by stepping to recover upon the reslip. Thirty-six participants who stepped backward initially and upon the reslip altered their nonstepping limb reactive response to reduce hip vertical descent during the step (p < .001).

Conclusions. Young and older adults rapidly learned to avoid falling through similar proactive and reactive adaptations that persisted in the short term. Both proactive and reactive adaptations should be targeted in interventions to reduce older adult fall incidence.

Because falls are a significant cause of activity restriction, functional decline, injury, and death in older adults (1–3), effective means of preventing falls are needed. Fall incidence might be reduced through interventions focused on identified risk factors (4,5), improving general physical function (6,7), or reducing environmental hazards (8,9). However, an alternate approach might be to train older adults to better recover from or adjust to perturbations.

To investigate this latter possibility, young and older adults were repeatedly exposed to slips during a sit-to-stand task (10). Although more older than young adults fell upon the first, novel, and unexpected slip (73% vs 28%), fall incidence decreased at an age-independent exponential rate with repeated slip exposure. Furthermore, upon reexposure to slipping after a block of nonslipping trials, the odds of falling were 24.0 times lower than upon the first slip, regardless of age group. It remains unanswered, however, what adaptations were responsible for these decreases in falling.

Adaptations to avoid falling could include proactive adjustments to task performance before slip onset and/or altered reactive responses to slipping. Falls upon the first slip were associated with a backward loss of balance and an absent or diminished stepping response (11). The latter was characterized by a “collapse” of the nonstepping limb, leading to a lower hip height at step touchdown, and a stepping foot placement less posterior to the body center of mass (COM). Experimental (12), modeling (13), and verification (14) studies have indicated that proactive adjustments to task performance directly influence the likelihood of a backward balance loss upon a slip. Such proactive/anticipatory adjustments typically precede the onset of an expected postural perturbation and serve to counteract its expected destabilizing effect, reducing the reliance on reactive responses to avoid a fall (15–19). Alternately, changes in reactive response, including added or more effective compensatory stepping, could reduce the likelihood that a balance loss will result in a fall. Rapid adaptive changes in reactive responses upon repeated perturbation exposure, consistent with an enhanced ability to recover from the perturbation, have been observed in healthy young (20–23) and older adults (24,25). In fact, in older adults, learning to recover upon repeated exposure to a perturbation during standing has been associated with a decrease in reaction time and an increase in step length (26).

This study investigated whether the previously reported decrease in fall incidence with repeated slip exposure (10) was achieved through proactive and/or reactive adaptations. It was further examined whether these adaptations differed between age groups and whether they persisted upon later slip reexposure.

Methods

Participants

Forty-one healthy older adults (21 women) and 60 healthy young adults (44 women), described previously...
(10), gave written informed consent and were paid to participate. Older adults were community dwelling (mean ± SD [standard deviation] 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). Participants were screened for exclusionary factors that included neurological, musculoskeletal, and cardiopulmonary disorders. Older adults were screened for cognitive impairment, poor mobility, and orthostatic hypotension. Older adults whose calcaneal bone mineral density was assessed (Hologic Sahara, Bedford, MA) as osteopenic or osteoporotic were excluded. Institutional Review Board approval was obtained.

Experimental Protocol

The protocol has been detailed previously (10). Slips were induced during a sit-to-stand movement using a side-by-side pair of low-friction platforms (friction coefficient: 0.02) which were free to slide 24 cm forward upon release of their locking mechanisms. Platforms slid independent of each other and latched into place in their maximum forward positions. Although participants could slide the platforms relative to each other during a slip, at least 1 platform traveled the maximum distance in 99.5% of cases. Participants wore a full-body safety harness, attached to a ceiling-mounted support by a pair of shock-absorbing dynamic ropes. A load cell measured the force exerted on the ropes.

Trials began with participants sitting on a stool in a standardized position. The shoe feet rested a self-selected width apart on separate platforms, heels at the rear edges. Ankles were dorsiflexed 10°, knees were flexed 80°, and arms were at the sides with the elbows flexed 90°. Participants 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 trial, timing, and mechanisms of the slip were not provided. Participants were to stand up “as quickly as possible,” without using their arms. After 4 normal sit-to-stand trials, a slip was induced, without warning, early in the braking phase after seat-off; a computer simultaneously released both platforms when the stool supported less than 10% body weight and the body COM forward velocity exceeded 20 cm/s. Platform release data were computed in real time from 3 force plates (AMTI, Newton, MA) located beneath the stool and each platform, respectively, with COM velocity computed from the real-time time integral of the measured shear forces.

Following the first slip, participants were informed that a slip “may or may not occur” during subsequent trials. They were to “try not to fall,” then remain standing still afterwards. All other instructions were as before. No additional information was provided. Participants underwent 5 consecutive slipping trials, followed by at least 3 consecutive nonslipping trials; a fourth nonslipping trial was added if stepping occurred during the third. Participants were then reexposed to 2 slipping trials. The first such reexposure comprises the reslip.

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

Locations of joint centers, heels, and toes in 3-dimensional space were computed from the marker paths using transformations derived from anthropometric measurements and kinematic data collected during an initial quiet standing trial (27). The body COM was computed using sex- and age-dependent segmental inertial parameters (28,29) in a 13-segment, 3-dimensional representation of the body. Separate pelvis, torso, and head segments were included, with the torso and pelvis segmented at the level of L3–L4. The COM anterior position (X_{COM}) and forward velocity (V_{XCOM}), measured horizontally in the sagittal plane, were determined at seat-off of each slip. Seat-off was defined to occur when the vertical force on the stool dropped below 5% body weight, as measured by the underlying force plate. X_{COM} at seat-off was referenced to the more posterior heel and normalized to the base of support (BOS) length (the sagittal distance from the more posterior heel to the more anterior toe).

As before (10), slip outcomes were classified as falls if the midpoint between the hips descended within 5% body height of its initial seated height. 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. All other outcomes were considered harness affected. Qualitatively, all falls were backward, with the time of fall defined as the earlier of (a) when the average safety harness force first exceeded 4.5% body weight over the preceding 1-second period or (b) 66 ms before the end of the first descent of the hip midpoint below the fall criterion.

Where stepping occurred, the length and direction (forward or backward) of the initial step were determined by the change in the horizontal sagittal displacement of the stepping ankle with respect to the nonstepping ankle between step lift-off and touchdown. Also determined were the step time between step lift-off and touchdown and the average step velocity (step length/step time). Times of step lift-off and touchdown were visually identified based on the presence or absence of vertical force upon the force plates or, if touchdown occurred outside the force plates, from foot kinematic data. Only the initial step was analyzed. Steps in which lift-off occurred after the time of fall were excluded.

Responses prior to step lift-off were characterized by the time from slip onset to step lift-off, the maximum BOS length prior to step lift-off, and the changes in X_{COM} and V_{XCOM} between seat-off and step lift-off, referenced to the position and velocity of the nonstepping heel, respectively. Slip onset was 25 ms before the displacement of either platform from its mean prerelease position exceeded three times the standard deviation of its position data in the period prerelease. Responses of the nonstepping limb were characterized by the changes in the hip midpoint height and nonstepping knee flexion angle, measured in the sagittal plane, between step lift-off and touchdown. Finally, the
computed $X_{COM}$ relative to the stepping heel was determined at step touchdown, together with the hip midpoint height.

**Statistics**

Effects of age group and trial on $X_{COM}$ and $VX_{COM}$ at seat-off, from the trial preceding the first slip through the reslip, were tested using two-factor repeated-measures analysis of variance (ANOVA). Post hoc $t$ tests identified age differences, and, within each age group, paired $t$ tests identified changes between consecutive trials and between the first slip and reslip. Bonferroni corrections were applied.

A multivariable logistic regression analysis determined the relationship between $X_{COM}$ and $VX_{COM}$ at seat-off and the likelihood of falling upon slipping, based on pooled data from all slip and reslip trials (excluding harness-affected outcomes). A multivariable, multinomial logistic regression analysis also determined the relationship between $X_{COM}$ and $VX_{COM}$ at seat-off and the likelihood of using an initial forward step or backward step, versus no step (the reference category), to successfully recover from a slip. Data from all recoveries in the slip and reslip trials were pooled for this analysis. Effects of age group and its interactions with $X_{COM}$ and $VX_{COM}$ were considered in both logistic analyses. Incidences of falling and stepping were predicted from the logistic equations using threshold probabilities of 0.5 for classification.

Changes in response between the first slip and reslip were investigated, as a function of age group and first slip outcome, among participants who stepped backward initially in both trials and recovered in the latter. Three-factor repeated-measures ANOVA, with appropriate post hoc analysis, were performed on each of 10 response-related variables described earlier. To control for family-wise error across this set of analyses, effects were considered significant at the .02 level. Contributions of proactive and/or reactive adaptations to each significant between-trial change among the 10 response-related variables of these participants were assessed through hierarchical linear regressions upon the pooled data from the first slip and reslip. The first block of predictors, $X_{COM}$ and $VX_{COM}$ at seat-off, assessed the effects of proactive adjustments in sit-to-stand performance upon each response-related variable that differed between the first slip and reslip. Systematic between-trial changes in reactive response were modeled as additive effects of trial (first slip vs reslip) and age (young vs older) in the second block of predictors added. The remaining blocks assessed the propagation of proactive and reactive effects through the response; the third and fourth blocks of predictors comprised the response-related variables that differed between trials in the periods prior to step lift-off and between step lift-off and touchdown, respectively. Post hoc logistic regression analysis then determined the influences of $X_{COM}$ and hip height at step touchdown on the likelihood of falling.

When, on occasion, a slip did not occur due to equipment malfunction or experimenter error, trials performed out of the normal sequence were excluded from analysis. Data for 9 young adults were excluded due to persistent problems or missing first slip data. Analyses were performed using SPSS 10.0 (Chicago, IL). A significance level of .05 was used unless otherwise specified.

### RESULTS

Both young and older adults adjusted their sit-to-stand performance with repeated slip exposure (Figure 1). Increases in $X_{COM}$ and $VX_{COM}$ at seat-off occurred after each of the first 2 slip trials, with a corresponding decrease after the first subsequent nonslip trial. Adjustment magnitudes differed between age groups ($p < .001$ for the trial-by-age...
ADAPTATIONS TO REPEATED SLIP EXPOSURE

Interactions), such that, after the first slip, the age-difference in \(X_{\text{COM}}\) disappeared and \(VX_{\text{COM}}\) of the young became persistently greater than that of the older adults. At seat-off of the reslip, \(X_{\text{COM}}\) and \(VX_{\text{COM}}\) of the young were greater than upon the first slip (both \(p < .001\)), whereas only \(X_{\text{COM}}\) was greater in the older adults (\(p < .01\)).

These proactive adjustments to sit-to-stand performance appeared to contribute to the reported decreases in fall incidence with repeated slip exposure (10), as greater \(X_{\text{COM}}\) and, in older adults, greater \(VX_{\text{COM}}\) at seat-off were associated with decreased likelihoods of falling (Figure 2). Across all slips and reslips, 35% of 23 falls and 99% of 300 recoveries by young adults and 48% of 54 falls and 95% of 222 recoveries by older adults could be correctly classified based on \(X_{\text{COM}}\) and \(VX_{\text{COM}}\) at seat-off and age group. Furthermore, predicted effects of between-trial adjustments in \(X_{\text{COM}}\) and \(VX_{\text{COM}}\) at seat-off paralleled the actual changes in fall incidence (Table 1). Nevertheless, actual fall incidence by young and older adults upon the first slip was 9% and 21% higher than predicted, respectively.

Adjustments to sit-to-stand performance also appeared to influence the incidence and initial direction of stepping during successful recovery (10). Increases in \(X_{\text{COM}}\) and/or \(VX_{\text{COM}}\) at seat-off were associated with a decreased likelihood of backward stepping and an increased likelihood of forward stepping (Figure 3). No-step recoveries were associated with intermediate combinations of \(X_{\text{COM}}\) and \(VX_{\text{COM}}\), with the thresholds for predicted stepping dependent on age group. Across all slips and reslips, 55% of 171 backward-step recoveries, 24% of 90 forward-step recoveries, and 80% of 261 no-step recoveries were correctly classified based on \(X_{\text{COM}}\) and \(VX_{\text{COM}}\) at seat-off and age group.

As reported (10), the odds of falling upon the reslip were 24.0 times lower than upon the first slip (\(p = .001\)), regardless of age group. Among 34 participants who experienced a backward fall upon the first slip but recovered upon the reslip, 17 altered their stepping behavior entirely between trials: from an initial backward step to no step or vice versa (Table 2). Those who employed an initial backward step in both trials (repeat steppers) were examined for between-trial differences in the reactive response after slip onset.

Changes in the responses of the repeat steppers between the first slip and reslip were evident in 5 of the 10 variables investigated (Table 3). Upon the reslip, there was less \(X_{\text{COM}}\) posterior displacement relative to the BOS during the 382 ± 161 ms from slip onset to step lift-off. Thereafter, in the 96 ± 5 ms between step lift-off and touchdown, repeated steppers exhibited less hip vertical descent and less nonstepping knee flexion upon the reslip. Finally, despite no between-trial changes in step length or step average velocity, \(X_{\text{COM}}\) was more anterior to the stepping foot and hip height was greater at step touchdown upon the reslip. A decrease of 1% body height in hip height or of 1% foot length in \(X_{\text{COM}}\) at step touchdown increased the odds of falling by factors of 6.0 (\(p = .01\)) and 1.03 (\(p = .002\)), respectively.

The changes in response appeared to result from both proactive adjustments to sit-to-stand performance before slip onset and adaptive changes in the reactive response after slip onset (Table 4). Each of the kinematic changes observed between the first slip and reslip was linearly related to the increases in \(X_{\text{COM}}\) and/or \(VX_{\text{COM}}\) at seat-off between trials, consistent with a causal effect. However, beyond these influences of sit-to-stand performance was an added effect of trial (first slip vs reslip) upon knee flexion and hip vertical descent during the step (Table 4).

Table 1. Correspondence Between the Actual Percentage of Slips That Resulted in Falls in Each Trial and the Percentage of Falls Predicted by the Derived Logistic Relationship Based on \(X_{\text{COM}}\) and \(VX_{\text{COM}}\) at Seat-Off and Age Group (Figure 2)

<table>
<thead>
<tr>
<th>Trial</th>
<th>Young Adults (N = 51)</th>
<th>Older Adults (N = 41)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slip 1</td>
<td>Actual %</td>
<td>33.3</td>
</tr>
<tr>
<td></td>
<td>Predicted %</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>N</td>
<td>76.3</td>
</tr>
<tr>
<td>Slip 2</td>
<td>10.4</td>
<td>22.1</td>
</tr>
<tr>
<td></td>
<td>9.8</td>
<td>41</td>
</tr>
<tr>
<td>Slip 3</td>
<td>2.5</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>Slip 4</td>
<td>2.2</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>40</td>
</tr>
<tr>
<td>Slip 5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>2.6</td>
<td>39</td>
</tr>
<tr>
<td>Reslip</td>
<td>2.0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>22.5</td>
<td>40</td>
</tr>
</tbody>
</table>

Notes: Harness-affected participants were excluded from all percentages and predictions for a given trial. \(X_{\text{COM}}\) = center of mass anterior position; \(VX_{\text{COM}}\) = center of mass forward velocity.

Figure 2. Relationship between \(X_{\text{COM}}\) (center of mass [COM] anterior position) and \(VX_{\text{COM}}\) (COM forward velocity) at seat-off and slip outcome. Data from all slip and reslip trials by 51 young (Yng) and 41 older (Old) participants are shown according to age group and trial outcome. A logistic model found significant effects of \(X_{\text{COM}}\) at seat-off (\(p < .001\)), age group (\(p < .001\)), and interactions of age group with \(X_{\text{COM}}\) and \(VX_{\text{COM}}\) at seat-off (\(p = .004\) and \(p < .001\), respectively) on the likelihood of falling. Model-predicted contour lines corresponding to a 50% likelihood of falling are shown for young (gray line) and older adults (black line), with the predicted trial outcome indicated on each side of the line. BOS = base of support length.
ences in XCOM and VXCOM at seat-off, an added effect of age interactions). Nevertheless, after accounting for age differences between young and older adults (Table 3), no change between the first slip and reslip differed between age groups ($p > .02$ for all age group interactions). Nevertheless, after accounting for age differences in XCOM and VXCOM at seat-off, an added effect of age was observed in 3 of 5 variables that differed between the first slip and reslip, consistent with an age difference in reactive response (Table 4). Responses of older adults were associated with greater COM posterior displacement relative to the BOS prior to step lift-off and a more posterior COM and lower hip height at step touchdown.

**Discussion**

Our previous analysis of these participants (10) found that, although more older than young adults fell upon the first, novel, and unexpected slip, fall incidence decreased at an age-independent exponential rate with repeated slip exposure. Furthermore, upon the reslip after 3–4 nonslipping trials, fall incidence in both age groups was less than upon the first slip. The present results indicate that the reductions in fall incidence with repeated slipping and upon the reslip were achieved through both proactive adaptations of sit-to-stand task performance and adaptive changes in the reactive response to slipping.

Proactive adaptations of task performance to reduce the likelihood of falling were evidenced by changes in XCOM and VXCOM at seat-off. Because seat-off preceded slip onset, these changes at seat-off reasonably reflect changes in the feedforward motor programming of task execution. After each of the first 2 slip trials, both young and older adults made adjustments that increased XCOM and VXCOM at seat-off. These served to simultaneously decrease the likelihoods of falling and of using an initial backward step to recover. Although subsequent exposure to nonslipping trials produced the opposite adjustments to XCOM and VXCOM, participants did not return to their original, first-slip sit-to-stand performance; XCOM and, in young adults, VXCOM were greater at seat-off of the reslip than upon the first slip.

Such proactive adjustments make sense. Slips resulted in an anterior translation of the bipedal BOS, acting to cause a backward balance loss. However, if XCOM and/or VXCOM at seat-off were made large enough, the COM would have sufficient momentum to reach the BOS, despite the slip, and a backward balance loss and potential backward fall could be avoided (12,13). Yet these proactive changes do not guarantee recovery. Notably, the likelihood of falling was unrelated to VXCOM at seat-off in young adults because 5 young adults suffered a second backward fall, or more, despite making proactive adjustments that greatly increased VXCOM at seat-off. Of 8 falls by these repeat fallers after their first, 7 are those with the largest VXCOM in Figure 2.

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Also, as seen in the stepping data, too large an XCOM or VXCOM could result in a forward balance loss due to an inability to terminate the COM momentum within the BOS. Forward balance losses are of lesser concern, however, since

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**Table 2. Cross-Tabulation of the Outcomes and Stepping Behaviors Upon the First Slip and Reslip Trials**

<table>
<thead>
<tr>
<th></th>
<th>Recover on Reslip</th>
<th>Fall on Reslip</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Back step</td>
<td>No step</td>
</tr>
<tr>
<td>Young Adults ($N = 51$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recover on 1st slip</td>
<td>Back step</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>No step</td>
<td>—</td>
</tr>
<tr>
<td>Fall on 1st slip</td>
<td>Back step</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>No step</td>
<td>1</td>
</tr>
<tr>
<td>Older Adults ($N = 41$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recover on 1st slip</td>
<td>Back step</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>No step</td>
<td>—</td>
</tr>
<tr>
<td>Fall on 1st slip</td>
<td>Back step</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>No step</td>
<td>7*</td>
</tr>
</tbody>
</table>

**Notes:** *Includes one participant who stepped 6.0 cm forward during a backward fall upon the first slip.*

Each entry indicates the number of participants within an age group that exhibited a given combination of outcomes and initial step directions in the two trials. Participants whose outcome was harness-affected in either trial are not included.
falls are much less likely to result from forward than backward losses (30). In fact, no forward falls occurred. Without receiving any instruction or guidance, both young and older adults immediately identified and made similar and appropriate proactive adjustments. The young adjusted to a greater extent, however; after the first slip, X\textsubscript{COM} was no longer more posterior and VX\textsubscript{COM} was persistently greater in young versus older adults at seat-off. Age-related declines in functional capacity, including lower extremity strength and power (31–34), could have limited the extent to which older adults could adjust. Alternately, the differences in adjustment might be related to the heightened tendency of older adults to step when perturbed (35,36). Whether due to decreased functional capacity or to changes in actual or perceived stability, the range of X\textsubscript{COM} and VX\textsubscript{COM} at seat-off for which older adults would likely recover without stepping was smaller than for the young. As a result, if older adults had made the same adjustments as the young, they would have closely approached their predicted threshold for forward stepping in Figure 3. Instead, older adults made different adjustments that were associated with a lower likelihood of forward stepping. The age groups nevertheless achieved similar exponential reductions in fall incidence through these differing adjustments, suggesting, together with previous findings (12), that young adults actually tended to overcompensate.

From the third slip through the reslip, actual fall incidence corresponded well with that predicted based on X\textsubscript{COM} and VX\textsubscript{COM} at seat-off. Yet upon the first, novel, and unexpected slip, actual fall incidence by young and older adults was 9% and 21% higher than predicted, respectively. Arguably, factors unrelated to sit-to-stand performance, namely deficiencies in reactive response, were responsible for this greater-than-expected initial fall incidence. That this discrepancy attributable to response deficiencies vanished in later slips suggests that changes in reactive response occurred between the first and later slips. Although not reported here, the data support such changes. Ten young and 20 older adults who fell upon the first slip recovered upon the second. Among these participants, 4 older adults who did not step in the first trial stepped in the second, while the 5 young and 10 older adults who stepped backward in each trial exhibited the same set of significant changes in response reported in Table 3 (the 11 remaining participants

<table>
<thead>
<tr>
<th>Variable, Event</th>
<th>Recover on 1st Slip (N = 15)</th>
<th>Fall on 1st Slip (N = 7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X\textsubscript{COM}, seat-off</td>
<td>0.6 ± 8.7</td>
<td>2.0 ± 9.6</td>
</tr>
<tr>
<td>VX\textsubscript{COM}, seat-off</td>
<td>22.9 ± 3.3</td>
<td>23.7 ± 2.4</td>
</tr>
<tr>
<td>Slip onset to LO (ms)</td>
<td>317 ± 53</td>
<td>371 ± 93</td>
</tr>
<tr>
<td>Max. BOS to LO (%ft len)</td>
<td>116 ± 12</td>
<td>119 ± 11</td>
</tr>
<tr>
<td>ΔX\textsubscript{COM}, to LO (%ft len)</td>
<td>−40.7 ± 19.3</td>
<td>−46.6 ± 15.8</td>
</tr>
<tr>
<td>ΔVX\textsubscript{COM}, to LO (%bh/s)</td>
<td>−56.8 ± 36.0</td>
<td>−67.8 ± 40.4</td>
</tr>
<tr>
<td>ΔZ\textsubscript{HIP}, LO→TD (%bh)</td>
<td>−1.2 ± 0.7</td>
<td>−2.7 ± 1.9*</td>
</tr>
<tr>
<td>Δθ\textsubscript{KNEE}, LO→TD (deg)</td>
<td>3.0 ± 11.6</td>
<td>7.2 ± 8.3</td>
</tr>
<tr>
<td>Step length (%bh)</td>
<td>10.2 ± 5.7</td>
<td>6.2 ± 3.2</td>
</tr>
<tr>
<td>Step velocity (%bh/s)</td>
<td>91.6 ± 44</td>
<td>74.6 ± 26</td>
</tr>
<tr>
<td>X\textsubscript{COM}, TD (%ft len)</td>
<td>15.3 ± 18.5</td>
<td>−8.4 ± 25.3</td>
</tr>
<tr>
<td>Z\textsubscript{HIP}, TD (%bh)</td>
<td>49.9 ± 1.3</td>
<td>44.0 ± 1.9*</td>
</tr>
</tbody>
</table>

Notes: *p < .05 vs 1st slip.
1p < .01 vs 1st slip.
2p < .01 vs recover on 1st slip.
3p < .01 vs young.
4With respect to the posterior heel at seat-off, nonstepping heel at LO, stepping heel at TD.
5**Corresponds to full knee extension.

Data are reported by age group and outcome of the first slip; all participants shown recovered upon the reslip.
recovered with a forward step or no step upon the second slip). Such rapid adaptive changes in reactive responses upon repeated perturbation exposure, consistent with an enhanced ability to recover from the perturbation, have often been observed in healthy young (20–23) and older adults (24–26). Of greater interest with respect to fall prevention is whether these changes in reactive response persist upon later reexposure to the perturbation. We therefore concentrated on the changes between the first slip and reslip.

Thirteen young and 21 older adults who fell upon the first slip successfully recovered upon the reslip. Ten such participants (5 young, 5 older) recovered without stepping upon the reslip, suggesting that proactive adaptations of task performance were primarily responsible for their learned ability to avoid a backward fall. Conversely, 1 young and 7 older participants fell without taking a needed backward step upon the first slip, but stepped backward to recover upon the reslip. Arguably, these participants learned to avoid falling by responding to a slip with the addition of an appropriate reactive stepping response.

All others who fell upon the first slip and recovered upon the reslip employed an initial backward step in both cases. The results indicate that these repeat steppers avoided falling upon the reslip through both proactive adaptations of task performance and altered reactive responses. Falls in both age groups upon the first slip were related to a “collapse” of the nonstepping limb, leading to a lower hip height at step touchdown, and a stepping foot placement less posterior to the COM (11). The present results indicate that proactive increases in VxCOM at seat-off acted to decrease the extent of backward COM motion prior to initial step lift-off. The subsequent decrease in nonstepping knee flexion and hip vertical descent during the step was associated both with the proactive increases in XCOM and/or VxCOM at seat-off and with altered reactive responses in the nonstepping limb. Finally, the proactive changes at seat-off and altered reactive responses were both associated, directly and by way of the changes in nonstepping knee flexion and hip height during stepping, with a higher hip height and more posterior stepping foot at touchdown in the reslip, facilitating recovery.

Interestingly, these proactive and reactive changes between the first slip and reslip were not limited to those who fell upon the first slip; the repeat steppers who recovered upon the first slip made essentially the same changes. The only differences were that those who originally fell exhibited a greater reduction in hip vertical descent and a greater increase in hip height at step touchdown between the first slip and reslip, indicative of a greater change in the nonstepping limb reactive response (since the proactive changes did not differ). Nevertheless, even those who recovered upon the first slip learned to reduce their likelihood of falling with repeated slip exposure.

Furthermore, these same between-trial proactive and reactive changes were observed in both age groups; young and older adults adapted similarly to repeated slip exposure. Evidence indicates that motor learning from prior outcomes is similar in young and older adults (37,38), but older adults typically exhibit poorer performance during and after learning (38,39). Consistent with this, 6 variables exhibited a persistent age difference across the first slip and reslip, with each difference, particularly those in hip height and XCOM at step touchdown, in a direction that might place the older adults at a greater risk of falling. Hence, as indicated by the age difference in fall incidence upon the reslip (10), older adults continued to show a relative deficit in the ability to recover after repeated slip exposure.

Notably, observed changes in reactive response among repeat steppers were limited to the nonstepping limb. Instead of hip vertical descent and nonstepping knee flexion during the step, there was a net ascent and extension, respectively, suggesting that participants had learned to react with a more
forceful extension of the nonstepping knee and/or hip. Surprisingly, the reaction time to step lift-off, step execution time, step length, and average step velocity remained unaltered between the first slip and reslip. Adjustments to task performance and changes in the nonstepping limb response effectively allowed the same step to succeed where it had failed earlier, further emphasizing the important roles of the body’s state at perturbation onset and of the nonstepping limb in recovery (40,41). Studies of expected perturbations have observed an invariance in step latency, length, and duration during repeated successful recoveries (23); however, in older adults, learning to recover from a forward perturbation included a decrease in reaction time and an increase in step length (26). The present invariance may be related to uncertainties in stepping response necessity and direction, particularly since the first slip and reslip were both preceded by nonslipping trials without stepping. Alternately, the invariance in step length could be related to perceived environmental constraints associated with avoiding stepping into the stool.

It should be considered that the present results are based on a population of healthy, community-dwelling older adults. A lesser ability to adapt might be observed in frailer populations with impaired strength, mobility, or cognition. Furthermore, this study investigated the adaptations that resulted upon repeated exposure to a single perturbation during a single task within a single experimental session. The extent to which such adaptations would transfer to the recovery from perturbations of different types, magnitudes, and directions during different activities of daily living is unknown. The extent to which the adaptations persisted beyond the experimental session is also unknown. These issues must be addressed before the potential for preventing falls by training the proactive or reactive behavior of older adults can be established. Nevertheless, the fact that such training was effective within the present limitations is encouraging.

Proactive and reactive adaptations each have an important role in fall prevention. Reactive adaptations can reduce the likelihood that a balance loss will lead to a fall, whereas proactive adaptations can eliminate the occurrence of balance loss entirely. Proactive adaptations can be highly effective when the direction of a perturbation is foreseeable and can lead to “desirable” movement patterns that allow balance to be maintained under both perturbed and unperturbed conditions (12–14). However, when a perturbation is less certain, reactive responses may play the dominant role in avoiding a fall. The present results found evidence that young and older adults exhibit similar adaptations in both proactive and reactive behavior with repeated exposure to a perturbation. The results indicate that both adaptations occurred simultaneously and were jointly responsible for the previously observed decrease in fall incidence with repeated slip exposure (10). In addition, both adaptations persisted to a significant extent upon later reexposure. Most adaptation in reactive response appears to have occurred over the first 2–3 slips, with changes in falling behavior thereafter explained predominantly by proactive changes in task performance. It may thus be argued that both proactive and reactive adaptations should be targeted in interventions to reduce fall incidence in older adults.

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