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Inoculation Against Falls: Rapid Adaptation By Young And Older Adults To Slips During Daily Activities

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Abstract

Objective—To determine whether aging diminishes one's ability to rapidly learn to resist falls on repeated-slip exposure across different activities of daily living.

Design—Quasi-experimental controlled trial.

Setting—Two university-based research laboratories.

Participants—Young (n=35) and older (n=38) adults underwent slips during walking. Young (n=60) and older (n=41) adults underwent slips during sit-to-stands. All (N=174) were healthy and community-dwelling.

Intervention—Low-friction platforms induced unannounced blocks of 2–8 repeated slips, interspersed with blocks of 3–5 nonslip trials, during the designated task.

Main Outcome Measures—The incidence of falls and balance loss. Dynamic stability (based on center-of-mass position and velocity) and limb support (based on hip height) 300 ms after slip onset.

Results—Under strictly controlled, identical low-friction conditions, all participants experienced balance loss but older adults were over twice as likely as young to fall on the first, unannounced, novel slip in both tasks. Independent of age or task, participants adapted to avoid falls and balance loss, with most adaptation occurring in early trials. By the fifth slip, the incidence of falls and balance loss was less than 5% and 15%, respectively, regardless of age or task. Reductions in falls and balance loss for each task were accomplished through improved control of stability and limb support in both age groups. A rapidly-reversible, age- and task-dependent waning of motor learning occurred after a block of nonslip trials. Adaptation to walk-slips reached steady-state in the second slip block, regardless of age.

Conclusions—The ability to rapidly acquire fall-resisting skills on repeated-slip exposure remains largely intact at older ages and across functional activities. Thus, repeated-slip exposure might be broadly effective in inoculating older adults against falls.

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Suppliers

Keywords

Aging; Learning; Motor skills; Postural balance; Rehabilitation

Increasing susceptibility to falls with age¹ poses a health threat to older adults. Injuries from falls affect not only frail people, but also healthy, active older adults.² One major cause of injurious falls is slipping, with slip-related falls responsible for nearly one fifth of hip fractures.³ It is therefore highly desirable to develop interventions that can inoculate older adults against slip-related falls during activities of daily living. A promising paradigm is that of learning through falling.⁴

As a prerequisite, such an intervention paradigm relies on the rapid adaptation of proactive adjustments and reactive responses to repeated perturbation, as is seen among young adults.^{5–8} In light of age-related sensorimotor deteriorations,⁹ it is essential to establish that older adults retain this ability to rapidly learn through experience. Preliminary evidence has shown that crucial fall-resisting skills can be rapidly acquired at an age-independent rate through repeated exposure to slips during a STS task.^{10, 11} In its early phases, such experiential learning typically exhibits a waning when exposure to a perturbation stops, resulting in a slight reversal of acquired performance.^{11–14} Despite this, when young and older adults who underwent repeated slips during a STS were reslipped after a set of nonslip trials, the odds of falls were 24-fold smaller than for the first, novel slip.¹¹ Furthermore, this single reslip produced an immediate re-acquisition of the previously-learned fall-resisting skills.¹¹ This learning was characterized by improvements in stability against balance loss and in limb support against unintended hip descent from seat-off through step touchdown,¹⁰ variables that have accurately predicted more than 90% of recovery outcomes to a novel slip during a STS.^{15, 16}

While these previous findings suggest that repeated-slip exposure could be an effective means of intervening against slip-related falls by older adults, important questions remain. Notably, walking, not a STS, is the primary task of concern for slip-related falls. It is unknown to what extent aging-related declines in sensorimotor function interact with the functional requirements of different tasks to influence the ability to learn to resist balance loss and falls. Also important is the extent to which the adaptations facilitated differ as a function of age. To be most effective in inoculating a person against falls, such adaptation should be age- and task-independent. There is further a need to establish whether older adults' adaptations to repeated slip and nonslip trials eventually mature to a steady state in which an enhanced ability to resist balance loss and falls remains essentially unchanged (i.e. neither wanes nor improves) over subsequent trials, as appears to occur in young adults.^{14, 17}

This study aimed to determine whether aging diminishes one's ability to rapidly learn to resist falls on repeated-slip exposure across different activities of daily living. The primary hypothesis was that the ability to rapidly acquire fall-resisting skills remains intact into older age, independent of task. We hypothesized that the adaptation would entail improvements in post-slip stability and hip height across age groups and tasks. We further expected this adaptation to show a rapidly-reversible waning after a block of nonslip trials, regardless of age group and task. Finally, we expected the adaptations to mature to a steady state over a number of slip and nonslip trials, as exemplified in this study for a walking task.

METHODS

Participants

Thirty-eight community-dwelling, healthy, older and 35 healthy, young adults participated in the walking portion of the study (Old-Walk and Young-Walk groups, respectively; Table 1).

Forty-one community-dwelling older and 60 young adults, described previously,¹¹ participated in the STS portion (Old-STS and Young-STS groups, respectively; Table 1). No individual participated in both portions. All participants walked without assistance, were free of musculoskeletal, neurological, cardiopulmonary, and other systemic disorders, as assessed through a questionnaire, and were screened for selected drug usage (e.g. tranquilizers). Tests administered by the research staff further excluded older adults with osteopenia or osteoporosis (based on calcaneal ultrasound),¹⁸ cognitive impairment,¹⁹ poor mobility (>13.5 s on the Timed-Up-and-Go test²⁰), or symptomatic postural hypotension. Thirty percent of older participants reported having fallen in the past year. Institutional Review Board approval was obtained and all participants provided informed consent.

Experimental Set-Ups

Slips during walking were induced in the Young-Walk and Old-Walk groups using a pair of side-by-side, low-friction, movable platforms embedded near the midpoint of a 7-m walkway. Platforms were free to slide forward up to 90 cm for older adults and up to 150 cm for young on release of their locking mechanism. The platforms latched into place on reaching these limits. Both platforms were released by computer just after right foot touchdown, as detected by 4 force plates^a located below them.

Slips during a STS were induced in the Young-STS and Old-STS groups using a pair of platforms similar to those used during walking, as reported previously.¹¹ On release, each platform was free to slide forward up to 24 cm before latching in place. Both platforms were released by computer just after seat-off, based on input from force plates beneath the stool and platforms. The coefficient of friction for all sliding platforms was less than 0.05.

Participants wore their own athletic shoes and a full-body safety harness throughout the experiment. The harness was attached to a ceiling mount, with a load cell^b installed in series to measure any applied forces. For walking trials, the ceiling mount was to a trolley positioned above the participant. The harness system was adjusted for each participant such that the knees and palms could not touch the floor.

Experimental Protocol

To start, Young-Walk and Old-Walk participants were instructed to walk with their preferred speed and manner. They were informed that they “may or may not be slipped” on any trial and that, if slipped, they should try to recover their balance and continue walking. After 10 trials of unperturbed walking, a slip was induced. No practice was given and participants were unaware of when, where, and how they would slip. After this first walk-slip, participants were instructed to continue walking in the same manner as they had been. They then completed 2 blocks of 8 slips and 2 blocks of 3 nonslip trials in an alternating manner, followed by a block of mixed slip and nonslip trials (Figure 1a).

STS trials by the Young-STS and Old-STS groups began with participants sitting on a stool in a standardized position with each foot on a sliding platform.¹¹ They were informed that they would initially perform STS trials and that a slip would occur “later.” Participants were to stand up “as quickly as possible,” without using their arms. After 4 unperturbed trials, a slip was induced. No practice was given and specifics of the slip were not provided. After this first STS-slip, participants completed 5 slips, 3–5 nonslip trials, then 2 more slips in blocked fashion (Figure 1b), told only that a slip might or might not occur on any trial and they were to try not to fall.

^a. AMTI, 176 Waltham St, Watertown, MA 02472.

^b. Sensotec, 2080 Arlingate Ln, Columbus, OH 43228.

Data Collection and Analysis

Position data were collected during walking at 120 Hz from 28 retro-reflective markers using an 8-camera motion capture system^c and during a STS at 60 Hz from 26 markers using a 4-camera system.^d Synchronously, load cell and force plate signals were recorded at 600 Hz. Marker paths were low-pass filtered at marker-specific cut-off frequencies. Locations of joint centers, heels, and toes were computed from the marker data. The body COM position was computed using sex- and age-dependent inertial parameters, with COM velocity calculated through numerical differentiation.

The anteroposterior position and velocity of the COM ($X_{\text{COM/BOS}}$ and $\dot{X}_{\text{COM/BOS}}$, respectively) were expressed relative to the respective position and velocity of the rear of the BOS. The rear of the BOS was considered the heel of the most recent foot to touch down for walk-slips and the heel of the posterior foot in ground contact for STS-slips. $X_{\text{COM/BOS}}$ was normalized to foot length and $\dot{X}_{\text{COM/BOS}}$ to $\sqrt{g \times h}$,²¹ where g is gravitational acceleration and h is body height.

Stability was calculated as the shortest distance from the COM state (i.e., $X_{\text{COM/BOS}}$ and $\dot{X}_{\text{COM/BOS}}$) to the previously published, model-derived limits of dynamic stability under slip conditions.²² The model predicts that backward balance loss must occur for COM states below the stability limits (stability < 0) and should not occur for those above the stability limits (stability > 0). Larger values indicate greater ability to resist backward balance loss.^{23, 24} Limb support by the stance limb(s) was quantified by the height of the midpoint of the two hip joint centers from the ground. Stability and hip height were both analyzed at 300 ms after slip onset, an instance that preceded the earliest recovery step touchdowns and at which these variables jointly predicted fall versus recovery outcomes of the first slip with ~70% accuracy.

For walk-slips, a fall was identified if the hip midpoint descended 15% body height below its minimum during unperturbed walking. For STS-slips, a fall occurred if the hip midpoint descended to within 5% body height of its initial seated height. Across tasks, a *recovery* was identified if the average force on the harness did not exceed 5% of body weight over any 1-second period after slip onset. Trials meeting neither the criteria of a fall nor a recovery were considered harness-affected and excluded from analysis. Three Old-Walk and 2 Old-STs participants were excluded due to harness-affected trials. Across tasks, a backward balance loss occurred if a participant fell or took a backward recovery step. For walk-slips, a backward step corresponded to the stepping toe landing posterior to the sliding heel. For STS-slips, it corresponded to the stepping ankle being posterior to the stance ankle at step touchdown.

Statistics

Initial adaptations to slipping were identified from the first 5 trials of the first slip block. Generalized estimating equation models were used to test linear and quadratic effects of trial (slips 1–5), effects of age-task group (Old-Walk, Young-Walk, Old-STs, and Young-STs), and trial by group interaction effects on the incidence of falls and backward balance loss. Adaptations in stability and hip height were examined using 3-way analyses of variance with trial (slips 1–5) as a within-subject factor and age (young vs. old) and task (walk-slips vs. STS-slips) as between-subject factors. Simple effects associated with significant 2-way interactions were investigated using independent or paired t-tests, with data pooled across the factor not involved in the interaction.

^c.Motion Analysis, 3617 Westwind Blvd, Santa Rosa, CA 95403.

^d.Peak Performance, 7388 S Revere Pkwy # 901, Englewood, CO 80112.

Waning and relearning of adaptations to slipping were characterized across the last trial of the first slip block and first 2 trials of the second slip block (first and second reslip, respectively). For each age-task group, the incidences of falls and balance loss were compared between trials using Wilcoxon tests. For each trial, age-differences in the incidence of falls and balance loss were identified for each task using Mann-Whitney tests. Corresponding changes in stability and hip height across the three trials were examined using 3-way analysis of variance with trial as a within-subject factor and age and task as between-subject factors. Significant interactions were investigated as described earlier.

To examine whether steady state adaptation to walk-slips was reached, Wilcoxon tests of the incidences of falls and balance loss were performed individually for the Young-Walk and Old-Walk groups between selected trial-pairs. These pairs were the second reslip and the last slip of the second block (slip 16), slip 16 and the first slip of the mixed block (slip 17), and slip 17 and the last slip (slip 24). Steady state adaptation was studied only in walking because of the limited number of trials in the STS-slip protocol. All analyses were performed using SPSS 15^e with a significance level of 0.05.

A post-hoc power analysis indicated that the present sample sizes provided a statistical power of 0.85 to detect a within-group effect size of 0.24 or greater and a between-group effect size of 0.38 or greater in each of the four outcome measures when using a two-sided alpha level of 0.05. These effect sizes were considered adequate to detect clinically relevant differences between experimental conditions.²⁵

RESULTS

Initial Adaptation

For both tasks, older adults fell at a higher rate than young across trials (age effect: $P < 0.01$ for each task; Figure 2a). Most notably, older adults were over twice as likely as young to fall on the first, unannounced, novel slip in both tasks (relative risk: $0.48/0.19=2.5$ for walk-slips and $0.73/0.33=2.2$ for STS-slips). Independent of age or task, however, participants adapted rapidly to avoid falls (trial linear effect: $P < 0.001$, Table 2), with most adaptation occurring in earlier trials (trial quadratic effect: $P < 0.05$). By trial 5, less than 5% of participants fell, regardless of age or task.

All participants experienced a backward balance loss on the first slip. However, independent of age or task, participants adapted to avert such balance losses (trial linear effect: $P < 0.001$; Table 2; Figure 2b) and most adaptation occurred in earlier trials (trial quadratic effect: $P < 0.001$). By trial 5, less than 15% of participants experienced a backward balance loss, regardless of age or task. No age-differences existed in the incidence of backward balance loss across trials (age effect: $P > 0.05$ for each task).

One mechanism of adaptation was improved control of stability across trials (Table 3; Figure 3). These improvements were independent of age, but differed slightly between tasks. While stability increased from trials 1 through 3 for both tasks, only STS-slips produced further improvements on trial 4. No age-differences in stability existed for either task.

Young and older adults also exhibited similar improvements in limb support across trials (Table 3; Figure 3). Independent of age, hip height increased in both tasks from trials 1 through 3, without further improvements thereafter. An age-difference in hip height was present for STS-slips but not walk-slips.

^e.SPSS Inc, 233 S Wacker Dr, 11th Fl, Chicago, IL 60606.

Waning and Relearning

The waning of motor learning after a block of nonslip trials was most prominent for STS-slips by older adults (Old-STS group); only this age-task group experienced more falls on the first reslip than on the last slip of the first block (Table 4; Figure 2a). Falls incidence on the first reslip was thus greater in older adults than young for STS-slips only. The Old-STS group rapidly relearned to avoid falls; only one fall occurred on the second reslip.

The incidence of backward balance loss increased between the last slip of the first block and first reslip in all age-task groups (Table 4; Figure 2b). Only for STS-slips, however, was balance loss incidence on the first reslip greater in older adults than young. Participants rapidly relearned the needed skills; irrespective of age-task group, fewer balance losses resulted on the second reslip than the first. For the walk-slips, this learning reached a steady state in that, from the second reslip onward, there were no detectable differences in balance loss or fall outcomes for the selected slip trial-pair comparisons (Figure 4; all $P > 0.05$).

The changes in balance loss across the reslips were accompanied by changes in the control of stability (Table 3; Figure 3). For each task, stability decreased from the last slip of the first block to the first reslip and then increased again on the second reslip. Also, while no age-difference in stability existed on the last slip of the first block, older adults had lesser stability than young on the first reslip. This age-difference was independent of task and disappeared on the second reslip.

Changes in limb support across the reslips were similar in young and older adults (Table 3; Figure 3). For each task, hip height decreased from the last slip of the first block to the first reslip and then increased again on the second reslip. An age-difference in hip height was present only for STS-slips.

DISCUSSION

The present results support the primary hypothesis that the ability to rapidly acquire fall-resisting skills on repeated-slip exposure remains largely intact at older ages and across different functional tasks. Older adults reduced their odds of falls by 7-fold during walking and 8-fold during a STS after only one slip exposure, paralleled by reductions in the incidence of balance loss and adaptive improvements in stability control and limb support. Although these fall-resisting skills were not fully retained after a block of nonslip trials, they were rapidly relearned and, as demonstrated for walking, reached a steady state in the second slip block. Similar to the “learning from falling” observed in early childhood,²⁶ the results indicated that, through the experience of slipping and falling, it may be possible to inoculate a person to reduce falls, even among older adults.

It was previously reported that older adults are more likely than young to fall from a novel, unannounced slip during a STS.¹¹ The present study extends that finding. Under strictly controlled, identical low-friction conditions, older adults were over twice as likely as young to fall on the first, unannounced, novel slip in both tasks tested, suggesting that this may be true to an extent across tasks in general. This increased vulnerability to falls could be a consequence of aging-related effects on sensorimotor function. Changes such as decreased muscle strength and power,²⁷ longer latencies, lower magnitudes, and increased burst durations of postural responses,²⁸ and attenuated neural excitability and weaker reflex torques,²⁹ have been implicated in heightened fall risk with aging. These deteriorations may alter older adults' regular movement patterns or weaken their reactions,^{9, 30} causing deficiencies in controlling slip severity, resisting limb collapse, and re-establishing stability,^{15, 31, 32} leading to more falls, regardless of task.

Despite their greater initial incidence of falls, the present older adults learned to resist balance loss and falls as rapidly as young adults on repeated-slip exposure. Furthermore, rates of adaptation did not differ between walk-slips and STS-slips, despite the different functional requirements of the tasks being performed. Hip vertical motion, COM horizontal motion, and BOS characteristics differ greatly between walking and a STS. These differences did not affect the ability of healthy older adults to learn to resist balance loss and falls. Nor did aging-related declines in sensorimotor function impair the ability to learn for one task more than the other. This suggests that, even in the unlikely scenario of an absence of generalization, repeated-slip exposure could still be applied across a variety of tasks to inoculate older adults against slip-related falls during those tasks.

It was also demonstrated that the adaptive mechanisms in response to repeated-slip exposure are similar for young and older adults and for both tasks. Across age groups and tasks, adaptations were characterized by improvements in both stability and limb support, causal factors that have been shown to play critical and differing roles in resisting falls.^{15, 16, 33} This rapid improvement between trials in stability and limb support 300 ms after slip onset likely resulted from feedforward adjustments to task execution and changes in reactive control, serving to increase $X_{COM/BOS}$ and $\dot{X}_{COM/BOS}$ at slip onset and reduce peak slipping velocity to ameliorate balance loss.^{5, 10, 31, 34} The mechanisms of adaptation were nearly task-independent. Although changes in stability and hip height were smaller and, for stability, slower (i.e. requiring more trials) for STS-slips than for walk-slips, especially among older adults, such disparities were dwarfed by the similarities.

Waning of the initial adaptations to slipping was observed regardless of age or task on the first reslip after a block of nonslip trials; however, stability decreased to greater extent in older adults for both tasks. In addition, for the STS task, more old than young adults exhibited balance loss and falls on the first reslip, suggesting that the short-term retention of adaptation is affected, to some degree, by age and task functional requirements. Yet relearning occurred by the second reslip and, as shown for walk-slips, rapidly reached a steady state in which the enhanced ability to resist balance loss and falls no longer waned with exposure to nonslip trials. These results suggest that facilitating a steady state adaptation that minimizes the kind of short-term waning observed on the first reslip may be crucial for effective inoculation against falls.

The requirements for inoculation against falls include not only rapid adaptation, but also the generalization and long-term retention of this learning. Similarities in motor programs presumably provide the basis for greater generalization of motor learning across tasks.³⁵ Although the present results provide evidence of similar adaptation across tasks, the extent to which older adults would transfer adaptations acquired in one task to recovery from different types, magnitudes, and directions of perturbations during different activities is unknown. Nevertheless, evidence exists among young adults that repeated-slip training of one limb can reduce fall incidence when the non-trained limb is slipped,³⁶ and that fall-resisting skills acquired on a moveable platform transfer to slips on a contaminated floor.³⁷ Evidence for young adults also indicates that fall-resisting skills acquired during one training session can be retained for at least four months.¹⁷ The extent to which the adaptations presently reported are generalized and persist among older adults after a single training session is yet to be investigated. Also unclear is the extent to which frail populations with impaired strength, mobility, or cognition can adapt to repeated slips. Differences between individuals or age-task groups in such characteristics as sex, body mass, physical function, activity level, and task performance (e.g. walking speed) were not presently accounted for. Nor is it known how experimental factors such as the safety harness, slip lengths, and trial sequences affected the results. It further remains to be confirmed that a steady-state adaptation to STS-slips will occur. Until such missing information is known, inoculation against falls remains, to some degree, simply an attractive concept.

CONCLUSIONS

Older adults retain their ability to rapidly adapt their control of dynamic stability and limb support to prevent slip-related falls. This ability prominently manifested itself during the performance of different daily activities, although some learning properties were detectably task-specific. Rapid adaptation is a prerequisite for the application of single-session, repeated-slip training to inoculate older adults against falls. The present findings suggest that such training might potentially be applied across a variety of tasks to inoculate older adults against slip-related falls during those tasks, providing an impetus for future investigations into the transfer and retention of these inoculations.

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List of Abbreviations

BOS	base of support
COM	center of mass
STS	sit-to-stand
$X_{\text{COM/BOS}}$	anteroposterior position of the COM relative to the BOS
$\dot{X}_{\text{COM/BOS}}$	anteroposterior velocity of the COM relative to the BOS

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a) Walk-Slip Protocol

b) Sit to Stand-Slip Protocol

Fig. 1.

Protocol for the a) walking and b) STS tasks. Blocks of slip trials (S) are shown in gray, blocks of nonslip trials (NS) in white, and the block of mixed slip and nonslip trials in vertical lines. For the walking task, the sequence of trials comprised 10 initial nonslipping (NS) trials, followed by a block of 8 slips, a block of 3 nonslipping trials, a second block of 8 slips, a second block of 3 nonslip trials, then a mixed block of 8 slip and 7 nonslip trials (S17–18, NS×2, S19, NS, S20, NS, S21–22, NS×2, S23, NS, S24). For the STS task, the sequence comprised 4 nonslip trials, followed by a block of 5 slips, a block of 3–5 nonslip trials (a 4th or 5th trial was performed if stepping occurred in the preceding trial), and a final block of 2 reslips (RS). For both tasks, all trials were unannounced, and participants were only aware that a slip “may or may not occur.”

Fig. 2.

Changes in the incidence of a) falls and b) backward balance loss with repeated exposure of young adults (OPEN symbols) and older adults (FILLED symbols) to slips during walking (squares) and during a STS (circles). Shown is the percentage of participants who fell or experienced a backward balance loss as a function of trial across the first slip block (S1 through S8 for walking; S1 through S5 for STS). The curves shown correspond to the models predicted by the generalized estimating equations (Table 2). Also shown are the incidence of falls and backward balance losses on the first and second reslip trials (S9 and S10 for walk-slips, RS1 and RS2 for STS-slips), induced after 3–5 nonslip trials. STS data from Pavol et al.¹¹ and Pai et al.²⁴

Fig. 3.

Trial-to-trial changes by young adults (OPEN symbols) and older adults (FILLED symbols) in a) stability during walk-slips, b) stability during STS (STS) slips, c) hip height during walk-slips, and d) hip height during STS-slips. Shown are the group mean $\pm$ 1SD results for the first through fifth slips of the first slip block (S1, S2, S3, S4 and S5), as well as for the first and second reslip trials (S9 and S10 for walk-slips; RS1 and RS2 for STS-slips) induced after 3–5 nonslip trials. All values correspond to 300 ms after slip onset. Stability in (a) and (b) was defined as the shortest distance from the center of mass state (i.e. its normalized anteroposterior position and velocity relative to the base of support) and the model-derived limits of dynamic stability under slip conditions.²² Stability is a dimensionless quantity, with more positive values indicating greater stability against backward balance loss.^{17,23} Hip height was measured from the ground to the midpoint of the two hip joint centers and was expressed as a fraction of body height (bh). * = $P < 0.05$ between trials. † = $P < 0.05$ between young and older adults.

Fig. 4.

Changes in the incidence of a) falls and b) backward balance loss with repeated-slip exposure during walking in young adults (OPEN squares) and older adults (FILLED circles). Shown is the percentage of participants who fell or experienced a backward balance loss during: the first and last slips of the first slip block (S1 and S8), the first, second, and last slips of the second slip block (S9, S10, and S16), and all the slips of the mixed block (S17 through S24). Also indicated are the occurrences and number of non-slip (NS) trials between blocks and within the mixed block. * = $P < 0.05$ between trials.

Table 1Mean $\pm$ SD Characteristics of the 4 Groups of Participants

	Group			
	Young-Walk	Old-Walk	Young-STS	Old-STS
<i>N</i>	35 (18 women)	38 (19 women)	60 (44 women)	41 (21 women)
Age (yr) [range]	26 $\pm$ 5 [18–37]	71 $\pm$ 5 [65–90]	25 $\pm$ 5 [18–41]	73 $\pm$ 5 [65–85]
Height (m)	1.67 $\pm$ 0.09	1.67 $\pm$ 0.10	1.69 $\pm$ 0.10	1.69 $\pm$ 0.09
Mass (kg)	63 $\pm$ 12	75 $\pm$ 14	67 $\pm$ 14	79 $\pm$ 14

Table 2
Parameter Estimates of the Generalized Estimating Equation Models of Falls and Backward Balance Loss

	Falls			Backward Balance Loss		
	Coefficient	Standard Error	P value	Coefficient	Standard Error	P value
Intercept	2.141	0.550	<0.001	7.338	0.602	<0.001
Group*						
Young-Walk (N = 35)	-1.670	0.635	0.01	-1.044	0.651	0.11
Young-STTS (N = 60)	-0.924	0.613	0.13	-0.343	0.699	0.62
Old-STTS (N = 39)	0.974	0.653	0.14	0.954	0.792	0.23
Trial (linear)	-2.403	0.446	<0.001	-4.372	0.328	<0.001
Trial (quadratic)	0.221	0.087	0.01	0.492	0.049	<0.001
Group × Trial Interaction						
Young-Walk × Trial	0.537	0.287	0.06	0.334	0.213	0.12
Young-STTS × Trial	0.108	0.351	0.76	-0.203	0.223	0.36
Old-STTS × Trial	-0.058	0.337	0.86	-0.066	0.239	0.78

* Reference group: Old-Walk (N = 35).

Post-hoc contrast analysis also indicated a significant group difference ($P < 0.01$) between Young-STTS and Old-STTS for Falls.

Table 3

P Values for the Effects of Age, Task, and Trial on Stability and Hip Height 300 ms After Slip Onset for the Initial Slip Trials (S1–S5) and the Reslip Trials

Effect	Stability		Hip Height	
	Trials S1–S5	Reslips	Trials S1–S5	Reslips
Age [*]	0.62	NA	NA	NA
Age × Task [†]	0.25	0.80	<0.001	<0.001
Age × Trial	0.41	0.04	0.44	0.12
Task × Trial	<0.001	0.005	0.002	0.002
Age × Task × Trial	0.52	0.48	0.61	0.06

^{*}Age = Young vs. Older;

[†]Task = Walk-Slips vs. STS-Slips;

NA = main effect not applicable due to a significant ($P < 0.05$) interaction effect involving Age. Stability is a dimensionless quantity and was defined as the shortest distance from the center of mass state (i.e. its normalized anteroposterior position and velocity relative to the base of support) to the model-derived limits of dynamic stability under slip conditions.²² Hip height was normalized to body height.

Table 4

P Values for the Effects of Trial and Age-Task Group on the Incidence of Falls and Backward Balance Loss During the Reslips

	Falls	Backward Balance Loss
Last Slip of 1 st Block vs. 1 st Reslip:		
Young-Walk	0.32	0.01
Old-Walk	0.32	0.03
Young-STS	1.00	<0.001
Old-STS	0.008	<0.001
1 st Reslip vs. 2 nd Reslip:		
Young-Walk	1.00	0.002
Old-Walk	0.32	0.03
Young-STS	0.22	<0.001
Old-STS	0.001	<0.001
Young-Walk vs. Old-Walk:		
Last Slip of 1 st Block	0.35	0.12
1 st Reslip	0.27	0.97
2 nd Reslip	1.00	0.43
Young-STS vs. Old-STS:		
Last Slip of 1 st Block	0.30	0.07
1 st Reslip	0.02	0.004
2 nd Reslip	0.41	0.09