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Prevention of Slip-Related Backward Balance Loss: Effect of Session Intensity and Frequency on Long-Term Retention

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Abstract

Objective—To examine effects of session intensity (number of slip exposures) and frequency on retention of acquired adaptation for prevention of backward balance loss following repeated-slip training.

Setting—Biomechanics research laboratory.

Participants—Healthy young subjects (N=46; 21 males).

Intervention—Twenty-four subjects experienced a high-intensity session of 24 repeated right-side slips; 12 received additional single-slip sessions at a frequency of 1-week, 2-week, and 1-month, while the rest got no ancillary training. Another 24 subjects received a low-intensity initial session of a single slip; 12 received the same high-frequency ancillary training, while the rest got none. All groups were retested with a single-slip, 4 months after first session.

Main Outcome Measures—Incidence of backward balance loss, gait stability, and limb support.

Results—The high-intensity groups irrespective of ancillary training displayed similar improvements in all 3 outcome measures. Remarkably, the low-intensity group receiving ancillary training also significantly improved in all measures, with retention comparable to that observed in the other 2 groups. A single slip exposure without ancillary sessions was insufficient to yield longer-term effect.

Conclusions—Frequent ancillary sessions may be unnecessary for slip-related fall prevention up to 4 months, if initial session intensity is sufficient. Furthermore, the minimum of a single slip may be as effective, if subject is exposed to frequent ancillary sessions.

Keywords

Accidental falls; Gait; Learning; Rehabilitation

The rising susceptibility to falling with increasing age^{1–3} poses a significant health threat to the older adult population. Falls are the leading cause of injury-related hospitalization leading to a decreased mobility and quality of life. Approximately 81% to 98% of hip fractures annually are caused by falls^{4,5} with slips comprising 40% of outdoor falls among community-living adults 70 years of age or older.⁶ These fractures require surgical intervention and extensive postsurgical management, at great cost both to patients and to the health care system.^{2,4,7–9}

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Suppliers

Thus, reducing the incidence of slip-related falls, which is frequently preceded by backward loss of balance, is essential.

General exercise-based, combined training paradigms (which could include either 1 or multiple components such as flexibility, strength, endurance, posture control, and balance training) are proposed as one method of improving older adults functional capacity and preventing falls and fall-related fractures in older adults.^{10–18} The fall reduction, though evident, has not always proved to be significant in the studies conducted.^{16,19–24} Similarly, although improvements in postural stability,^{26,27} or functional balance tests,²⁸ or the fall risk ratio^{23,29} with computerized balance training platforms have been linked to reduction of fall likelihood, evidence is lacking on the direct causal effect of such association.

In contrast, repeated slips induced during activities of daily living, such as sit-to-stand and walking, can directly reduce falls and balance loss incidence resulting from the improvements in a person's feed-forward and feedback control of dynamic stability displayed during the recovery from a slip.^{30–33} Dynamic stability is defined as ability to restore one's COM state (ie, its position and velocity) without altering his/her original or intended BOS following an externally imposed perturbation or volitional movement.³⁴ Recent findings, in adaptive response to repeated-slip training have revealed improvements in limb support, the second determinant of fall-recovery outcome in response to slips.^{35,36} While the dynamic stability can be quantified by comparing one's COM position and velocity (that is, its motion state) with the boundary against backward balance loss,^{37–39} limb support can be assessed based on the amount of descent in hip height following a slip.^{35,36} Limb support is defined as the amount of vertical support provided by the limbs to prevent unintended hip descent. The unintended hip descent is defined when hip is located 3 SDs below this person's average hip height in unperturbed gait, and when the hip velocity prematurely reverses in the downward direction.³⁴

Such repeated-slip training paradigms, though beneficial, may nevertheless be cumbersome and expensive to implement (eg, require slip inducing device and protective harness equipment, longer testing time, personnel skills, and liability for injury from simulated falls). Furthermore, this method also involves greater risk of injury than general exercise or nonperturbation-based training protocols (strength training, Tai-Chi, etc.). It is unclear the extent to which this new training paradigm can be further improved in terms of efficiency and risk reduction.

It is evident that practice schedules are an important consideration in motor learning. In particular, incorporating random practice (contextual interference)^{40–42} and overlearning (ie, continued practice of a task after having reached some success criterion)^{43–45} can lead to improved retention effects. For example, a single low acquisition session consisting of a brief exposure to a block of slips (5 slips only) without any additional ancillary sessions was insufficient to yield retention in stability for prevention of backward balance loss 12 months later.⁴⁶ Yet over learning by utilizing such principles as combined, blocked, and alternating practice (with an alternating slip, no-slip, and reslip paradigm), yielded significant retention of acquired improvements in stability and incidence of balance loss up to 4 months.³³ Our unpublished findings indicated that a similar retention may exist in limb support improvements. Such retention may result from 3 additional ancillary sessions, consisting of a single slip exposure at 1-week, 2-week, and 1-month intervals. It is unclear the extent to which the intensity of the initial session can be reduced but yet achieve the same level of retention. It is equally unclear whether ancillary training is needed to achieve such retention following a low-intensity initial training session, or whether it becomes unnecessary in a high-intensity one. Answers to questions such as these would improve the efficiency of fall-prevention training paradigms suitable for a variety of older adult populations ranging from the independent-living community to the older adults who may be frail or institutionalized. If the very minimum of a

single-slip exposure used in the initial and subsequent ancillary sessions could yield similar benefit as a high-intensity session, the frail adults who could not tolerate high repetitions may still be able to benefit from this emerging paradigm for fall prevention.³⁴ Furthermore, less slip exposure could, in itself, reduce the risk of training-related injuries.

The purpose of this study was to determine the effect of practice schedule (session intensity and training frequency) on longer-term retention (ie, up to 4 months) for prevention of balance loss and falls from a slip. Subjects were randomly assigned to 4 groups each consisting of a combination of intensity and frequency practice schedule. First, we hypothesized that a high session intensity (high-intensity, low-frequency) would prove to be efficient, such that there would be no measurable difference in performance improvements at the 4-month retest after their initial session, compared to improvements induced by the additional training frequency in the high-intensity, high-frequency group. Second, we hypothesized that low session intensity could prove as effective as high-intensity, however only when combined with high training frequency. Thus we expected that the measured performance improvements induced by the low-intensity, high-frequency training would be comparable to the high-intensity, low-frequency training, while the performance of the low-intensity, low-frequency training would be lower than the low-intensity, high-frequency or the high-intensity, low-frequency groups.

METHODS

Subjects

Forty six young subjects (26±5y, 21 males) participated in the study after being screened for exclusionary factors including neurologic, musculoskeletal, cardiopulmonary, other systemic disorders, and selected drug usage. The subjects were randomly divided into 4 groups: (1) high-intensity, high-frequency (24 slips on initial session and 3 ancillary single slip training sessions, n=13); (2) high-intensity, low-frequency (24 slips on initial session and no ancillary sessions, n=13); (3) low-intensity, high-frequency (single slip on initial session and 3 ancillary single slip training sessions, n=12); and (4) Low-intensity, low-frequency (single slip on initial session and no ancillary sessions, n=11). Prior to their participation, all subjects gave informed consent as approved by the institutional review board. One subject from the high frequency, low intensity, 1 from the low-intensity, high-frequency, and 2 subjects from low intensity, low frequency did not complete the 4-month retest and were excluded from the analysis.

Experimental Set-Up

Slips were induced by means of a device consisting of a movable component attached to a stationary metal beam structure (2.50×0.30×0.21m) anchored to the top of 2 rectangular force plates^a bolted to the ground. The movable component comprised a metal plate (0.65×0.30×0.006m, 2.6kg) and its support system.⁴⁷ This plate can be either locked for regular walking trials or released to simulate a slip. The friction coefficient of the device was consistently below .05, within its preset maximum travel distance. A second similar device was placed adjacent to the first for recording the ground reaction forces acting on the nonslipping limb. The top plate was locked and served as a decoy plate to camouflage the sliding plate. These devices were embedded in a 7-m walkway and hidden by the stationary platforms surrounding them.

Slips were induced by a computer-controlled release mechanism that unlocked the moveable platform at the beginning of each trial without the knowledge of the subject. Once released, the moveable platform was free to slide on the linear bearings for up to a maximum travel distance of 1.5m on the right. A computer program written in LabView^b was used for online

^aOR6-5-1000, AMTI, Newton, MA

monitoring of the GRF and generation of the lock-release signal. The subjects wore their own athletic shoes and a full-body safety harness attached to a manually driven trolley on a ceiling-mounted I-beam via an intervening load cell (fig 1).

Protocol

All, subjects, regardless of group performed 10 regular walking trials at a self-selected speed; in these trials, they were instructed to walk in their ordinary manner and informed that they “may or may not be slipped” on any trial. Subjects were also told that on the occurrence of a slip, they should try to recover their balance and continue walking. Without revealing the purpose, the experimenter adjusted each subject’s starting position after each trial, so that his or her slipping (right) foot would land entirely on the moveable plate at touchdown. All subjects were able to take at least 3 steps before stepping on the moveable plate. The first slip was induced on the eleventh trial, without explicit warning or practice.

Following the first slip, subjects having a high-intensity component in their practice schedule (ie, high-intensity, high-frequency and high-intensity, low-frequency groups) were exposed to a repeated slip training paradigm. The subjects were told that they may or may not be exposed to slipping on the subsequent trials. The entire training paradigm, including the first trial, consisted of a block of 8 repeated slips (S1–S8), a block of 3 nonslip trials (NS1–NS3), another block of 8 slips (S9–16), a second block of 3 nonslip trials (NS4–NS6), and a final block of 15 mixed trials. The sequence of the mixed block of trials was consistent for each subject: S17 and S18, NS7 and NS8, S19, NS9, S20, NS10, S21 and S22, NS11 and NS12, S23, NS13, and S24.³³

Following the initial session, subjects having a high-frequency component in their practice schedule (ie, high-intensity, high-frequency and low-intensity, high-frequency) were followed by 3 single-slip ancillary sessions conducted at intervals of 1 week, 2 weeks and 1 month. For each ancillary session, the setup and instructions were identical to those of the initial session. The protocol consisted of only one unannounced slip on the training (right) side induced after 8 through 13 regular walking trials. The instructions given to the subjects throughout the retests were also consistent with those given for the initial session.

All subjects returned for a retest session at 4 months post their initial session. The protocol followed was exactly similar to that used for the single-slip ancillary sessions, for example, 1 slip exposure after 8 through 13 regular walking trials. The exact return date for all the follow-up sessions was within 1 or 2 days of the scheduled date for the 1 week and 2 week sessions and 3 to 4 days beyond or short of a month, for the 1 month and 4-month sessions.

Data Collection and Reduction

A set of 24 full-body light-reflective markers was attached to the bilateral upper and lower extremities and the torso, while 1 marker was attached to each moveable platform. Marker coordinates were recorded at 120 Hz using a 6-camera motion capture system^c. Marker displacement data were low-pass filtered at marker-specific optimal cut-off frequencies (range, 4.5–9Hz) using a recursive second-order Butterworth Filter.⁴⁸ Force plate, harness load cell data, and trigger-release onset signal were collected at 600Hz using a 64-channel, 16-bit A/D converter. The ground reaction force data was time synchronized with the motion data externally at the time of data collection.

^bNational Instruments Inc., Austin, TX

^cMotion Analysis Corporation, Santa Rosa, CA

Backward Loss of Balance

The outcome of a slip trial was classified either as a backward loss of balance or no backward loss of balance. When the contralateral limb landed posterior to the sliding heel, with negative values in postslip step length during the slip, the trial was classified as a loss of balance trial with recovery stepping. Conversely, trials in which the contralateral limb landed anterior to the sliding heel (having positive postslip step length) were classified as “no loss of balance” trials, in which recovery stepping was not needed, and forward progression was not disrupted.⁴⁹ Analysis was restricted to the anteroposterior direction. The instances of step liftoff and touchdown were identified from the vertical ground reaction forces.

Gait Stability

The COM position and its velocity were computed from the kinematic data using known sex-dependent segmental parameter information in a 13-segment representation of the body.⁵⁰ The position of the COM in the anteroposterior direction was expressed relative to the rear of the BOS ($X_{COM/BOS}$) of the foot most recent to touchdown (ie, the heel of the sliding foot for slip onset) and normalized to foot length. The COM velocity in the anteroposterior direction was expressed relative to the velocity of the BOS ($\dot{X}_{COM/BOS}$) and normalized as a dimensionless fraction of

$$\sqrt{g \times h}^{51}$$

where g is the acceleration due to gravity and h is height of the subject.

Stability was assessed through comparison of the COM state relative to the BOS (ie, its position and velocity) with the previously published threshold values for backward balance loss under slip conditions.³⁸ Stability was defined as the shortest distance between this predicted boundary for backward balance loss and that of the instantaneous COM state.^{30,49} If the COM state is below the threshold (or to the left) the stability value will be negative, and vice versa if the COM state is above the threshold (or to the right) (fig 2) the stability value will be positive. If the COM state lies on the threshold it will have a stability value of 0. More positive values indicate greater stability against backward balance loss.^{30,49} Preslip stability was measured at touchdown of the slipping limb. Postslip stability was recorded at liftoff of the contralateral limb.

Limb support—The hip vertical motion has been previously associated with limb support.^{35,36} We therefore investigated the hip height. The hip height was defined as the height of the bilateral hip midpoint (obtained from the hip joint centers) to the surface of the platform. A lower hip height is indicative of poorer limb support, leading to a greater likelihood of falls following the slip.³⁶

Statistics—To test for measurable retention effects for incidence of backward balance loss, the Wilcoxon signed-rank test was performed between the initial session slip and the 4-month retest across the groups. Significance, if obtained was followed up with similar tests within each group. The main effect of group at each session was compared using the Kruskal-Wallis H test. The main effects of were resolved using the Mann-Whitney U test for between group comparisons at each session. Each recovery trial was categorized as a balance loss (value=0) or no balance loss (value=1) and analyzed as above.

To analyze the parametric outcome measures (pre- and postslip stability and hip height), an ANOVA for repeated measures was performed on each variable with session as the within-group repeated factor and these 4 predetermined groups (high-intensity, high-frequency; high-

intensity, low-frequency; low-intensity, high-frequency; and low-intensity, low-frequency) as the between-group factor. Significant main effects and interactions were resolved by performing planned within-group and between-group comparisons with paired and independent *t* tests, respectively. To test the effect of frequency, the high-intensity, high-frequency group was compared with high-intensity, low-frequency group and the low-intensity, high-frequency group with the low-intensity, low-frequency. To test the effect of intensity, the high-intensity, high-frequency group was compared with low-intensity, high-frequency and the high-intensity, low-frequency with low-intensity, low-frequency group. Lastly to examine the effects of frequency versus intensity the high-intensity, low-frequency group was compared to the low-intensity, high-frequency group. The statistical power and the partial η^2 (the proportion of total variability attributable to a factor) are reported for the ANOVAs. Absolute *P* values between .05 and .01 for the planned comparisons will be reported. A significance level of .05 was used for all the analyses. Analyses were performed using SPSS.

RESULTS

Backward Loss of Balance

There was a significant decrease in incidence of balance loss from the first slip to the 4-month retest between groups ($Z=-5.69$, $P<.001$) with a no difference in incidence of balance loss between groups on the first slip of the initial session ($\chi^2_{3,53}=0.00$, $P=1.0$), however a significant difference between groups at the 4-month retest ($\chi^2_{3,48}=8.05$, $P=0.04$). The analysis on the effect of session frequency clearly indicated that high-intensity training alone was sufficient for retention without the need for frequent ancillary sessions. The incidence of balance loss for subjects who had received high-intensity, low-frequency training remained significantly lower 4 months later as compared to their initial slip of the first session (100%–50%; $P<.001$). This training effect was very similar to subjects who received high-intensity and high-frequency training and who, as a group, reduced their incidence of balance loss from 100% at the first slip of the initial session to 39% at the 4-month retest ($P>.05$). As a result there was no difference in incidence of balance loss between the high-intensity, high-frequency and the high-intensity, low-frequency groups ($P>.05$).

Similarly, low-intensity training with high-frequency ancillary sessions in low-intensity, high-frequency group was shown to reduce incidence of balance loss from 100% at the initial session to 55% at the 4-month retest session ($P=.02$), with no difference between the low-intensity, high-frequency and the high-intensity, low-frequency and high-intensity, high-frequency groups ($P>.05$). In contrast, there was no improvement in the group receiving both, low-intensity and low-frequency training from the initial to the retest session (100% vs 78%, respectively; $P>.05$) (fig 3). At the retest, both high-intensity, low-frequency and low-intensity, high-frequency were noticeably better than the low-intensity, low-frequency group in resisting balance loss ($P=.05$ and $P=.07$, respectively), however, the difference between the high-intensity, high-frequency and low-intensity, low-frequency was the greatest ($P=.02$).

Stability and Limb Support

Similar results were demonstrated for the continuous variables, pre-and postslip stability and hip height. Preslip stability had a significant main effect for session ($F_{1,41}=31.62$, $P<0.001$, partial $\eta^2=0.43$, power=1), a significant session $\times$ group interaction ($F_{3,41}=3.23$, $P=0.03$, partial $\eta^2=0.2$, power=0.7), but no main effect for group ($F_{3,41}=1.008$, $P>0.10$, partial $\eta^2=0.07$, power=0.3). Postslip stability a significant main effect for session as well ($F_{1,41}=78.78$, $P>0.001$, partial $\eta^2=0.67$, power=1), a significant session $\times$ group interaction ($F_{3,41}=3.08$, $P=0.038$, partial $\eta^2=0.18$, power=0.68), with no main effect for group ($F^{3,41}=1.89$, $P=0.14$, partial $\eta^2=0.13$, power=0.45). Hip height also changed across sessions ($F^{1,41}=21.42$, $P<0.001$, partial $\eta^2=0.34$, power=0.99) with a significant session $\times$ group interaction ($F_{3,41}=2.82$,

$P=0.04$, partial $\eta^2=0.18$, power=0.64) and no main effect of group ($F_{3,41}=0.709$, $P>0.1$, partial $\eta^2=0.05$, power=0.2).

The retention in the both the high-intensity, low-frequency and high-intensity, high-frequency was accompanied by improvements in stability and in limb support (with higher hip height) when the first slip of the initial session was compared to the retest 4 months later ($P<.01$ for all variables for both groups) (fig 4A, B, and C). There was no between group difference in any of these variables ($P>.05$ for all comparisons). The low-intensity, high-frequency group also showed significant improvements in the pre- and postslip stability and in limb support from the initial to the 4-month retest session ($P<.01$ for all these measures). There was no difference in pre- and postslip stability and limb support between the high-intensity, low-frequency and low-intensity, high-frequency groups (no significant main effects or interaction, $P>.05$ for all variables). However both postslip stability and hip height were greater in the high-intensity, high-frequency compared to the low-intensity, high-frequency group ($P=.04$ for both comparisons).

In comparison to the training groups, however, there was no improvement in any of the variables at the 4-month retest in the group receiving low intensity and low frequency training in the form of a single slip ($P>.05$ for all variables). In comparison with the low-intensity, low-frequency group, both the high-intensity, low-frequency and low-intensity, high-frequency groups also had a significantly greater preslip ($P=.04$ for high-intensity, low-frequency, and $P=.03$ for low-intensity, high-frequency) and postslip stability ($P=.05$ for high-intensity, low-frequency, and $P=.04$ for low-intensity, high-frequency). Similarly, both groups had significantly better weight support, with a higher hip height than the low-intensity, low-frequency ($P=.04$ for high-frequency, low frequency; $P=.05$ for low-intensity, high-frequency) (see figs 4A, B, and C). The low-intensity, high-frequency had a significantly lower stability and limb support compared to the high-intensity, high-frequency group as well ($P<.05$ for all variables), with this decrease being most pronounced compared to the high-intensity, low-frequency and low-intensity, high-frequency groups.

DISCUSSION

In accordance with our hypothesis, the repeated-slip paradigm was efficient in improving performance to slips, such that the motor training induced by a single high-intensity session was retained for at least 4 months. The additional ancillary sessions did not yield significant benefits in stability control to reduce the incidence of backward balance loss, demonstrated by the comparable results found between the high-intensity, high-frequency and the high-intensity, low-frequency groups. Alternatively, in accordance with our second hypothesis, low-intensity training could also yield significant retention when combined with the ancillary sessions. This was demonstrated by the comparable performance between the low-intensity, high-frequency and the high-intensity, low-frequency groups. Nonetheless, a single slip alone, without any ancillary training, did not generate sufficient retainable benefits at 4 months.

Our findings from the first hypothesis were appealing, indicating that with sufficient stimuli from the high slip repetitions in a single session, the subject was able to retain the acquired motor skills for prevention of balance loss. Our previous findings have indicated a dominant role of stability and limb support (as measured by hip height) for recovery from slips during both tasks of sit-to-stand^{35,36} and gait (unpublished data). Subjects in both the groups receiving the intense session of repeated-slip training, showed a significant increase in both pre- and postslip stability, explaining the approximately 60% success rate in prevention of backward balance loss and diminished need for recovery stepping.³² The increase in hip height from the first slip of the initial session to the 4-month retest, further enhanced the success of recovery from slip by providing adequate limb support even under low friction conditions,

enabling subjects to maintain natural progression in stepping with their contralateral limb. It must be noted that postslip stability showed the greatest difference between the groups, which has been associated with most accurate prediction of incidence of balance loss,³² compared to the other 2 variables.

Although the finding that a single high-intensity training session can generate long-term retention is very promising, extrapolation of such a paradigm to a variety of populations may be premature. For example, individuals may not be able to tolerate such large number of slips (ie, about 40 trials with around 24 slips). However, results from our second hypothesis may prove to be promising in this situation. A single slip exposure when repeated frequently generated a cumulative effect resulting in significant increase in performance over a long period of 4 months. The results suggest that there is a coupling between the intensity of the initial session and the frequency of training where simultaneously increasing one and decreasing the other could yield similar effects, ultimately resulting in long-term retention of adaptive skills of preventing backward balance loss in slips.

The similar motor retention observed between the group that received a single session of high-intensity training and the group that received the high intensity training with frequent ancillary sessions is not surprising, and this finding can be explained based on emerging concepts on mechanisms of acquisition and storage of motor memory. It is proposed that the CNS acquires new sensory-motor relationships or strategies through the process of adaptation to enhance stability to cope with changes in external constraints and prevent incidence of balance loss and falls. Such a process is associated with building or modifying internal representation of one's stability limits for prevention of backward balance loss following forward BOS perturbations.^{30,32} Following repeated slips, adaptive improvements possibly shift from reliance on sensory feedback based error correction to a feedforward influenced, recalibrated control that regulates BOS perturbation kinematics and limb support.^{32,46} Such a shift would also result in developing an enhanced memory from the short-term labile state to a longer lasting stable state through the process of consolidation.⁵²⁻⁵⁵ Once in the consolidated stage, however, it is difficult to disintegrate the memory from interference resulting from competing or disrupting factors. It is proposed that a single session with sufficient training intensity, if by it self-served sufficient to induce permanent structural changes, additional training sessions even if provided, might not serve to induce any further changes in performance. The relatively constant performance previously demonstrated on each ancillary session by subjects who have received high-intensity training on the initial session, further supports this notion.³³

Our findings also indicated that the stored motor memory was subject to decay as demonstrated by the poorer retest results than those of the high-intensity, high-frequency and the high-intensity, low-frequency groups' twenty-fourth slip in the initial session. Apparently, providing additional ancillary sessions was not able to further prevent this decay in the high-intensity, high-frequency group. Our previous findings indicated that motor memory decay was associated largely with postslip stability control rather than with feedforward control of preslip stability.³³ Motor memory decay may be affected by subjects' inability to retain the minimal feedback based reactive control, still needed postslip, to control the BOS perturbation intensity once perturbation onset occurs.³² Such evidence suggests that adaptation in feedback control mediated by reflex responses may not be transformed into permanent representations similar to that of triggered responses or motor programs within the nervous system. Regular gait pattern is re-enforced on a daily basis, and may be the interference in the consolidation processes, leading to decay in motor memory of the training-acquired gait pattern. The performance of the high-intensity, low-frequency and high-intensity, high-frequency groups was still significantly better than that of the first slip in the initial session, indicating retention still outweighed decay at that instant.

Our results further suggest that increments in motor memory could continue to occur over spaced time intervals, if the initial experience or training did not result in sufficient memory saturation, as demonstrated by the improvements in the low-intensity, high-frequency group. The session-to-session performance improved in the low-intensity, high-frequency group and appeared to resemble the learning process observed in the trial-to-trial improvements of the high-intensity training in the initial session for the high-intensity, low-frequency. Our previous results have indicated a trial-to-trial reduction in balance loss from 100% to less than 10% within 3 to 5 trials during the initial training with repeated slip exposure.^{32,33} We observed a similar trend of session-to-session improvement with the single-slip exposures in the low-intensity, high-frequency group spaced at least 1-week apart, where backward balance loss reduced from a 100% on the first slip to 67% at 1-week session, to 58% at 2-weeks, and about 40% at the 1-month training session (fourth slip exposure). With each slip exposure, the CNS can update its internal representation of stability limits to better control its COM state and prevent balance loss when experienced with a similar perturbation in future. The modification of the stability thresholds with each session, would simultaneously allow the memory to be consolidated, resulting in permanent changes, which are harder to fade away; explaining the additive effect of training seen in this group. It is postulated that consolidation of memory could be as fast as a few minutes to few hours to even as long as months.^{54,56} Thus the consolidation could have occurred rapidly using high-intensity, large repetition training, but could have also been achieved as a gradual process with low session intensity but high session frequency.

It is proposed that the adaptive effect generated by an environmental threat is proportional to its intensity or the severity of the consequences in case of a failure. Exposure to a single slip is sufficient to induce immediate adaptive changes such that approximately 50% of subjects prevent incidence of balance loss and 80% of incidence of falls on the second slip of the same session.³³ The functional significance of the adaptation response, which itself is conditioned by the penalties imposed on an inappropriate response by the CNS and the increased potential of injury.^{57,58} Fear conditioning studies in mice have demonstrated that a single acquisition session is sufficient for long-term retention of the acquired stimulus-response behavior within the CNS.^{59,60} Thus, it was speculated if a single slip generated by our sliding device on the first session, having a large displacement and velocity profiles, could in itself be sufficient to induce longer-term retention lasting beyond a single session. Our results indicated otherwise, where a single slip could not significantly reduce incidence of backward balance loss on the 4-month retest. However, it must be noted that for 1 in 10 subjects this single slip was sufficient to induce longer-term memory changes such that he/she had an improved outcome to slip at 4 months.

The question still arises, however, if the findings revealed in the present study could be reproduced among healthy older adults or could be generalized to every-day life situations. Previous balance retraining studies have tested and observed improvements up to several months (4–6mo),^{13,23,28,61,62} however, the training was extensive consisting of several sessions per week continuing for several months.^{13,23,61,62} Further there is a limited correlation of such improvements with reduction in fall incidence. Evidence from motor learning for skilled voluntary tasks have indicated that older adults can completely retain an acquired skill for 2 years⁶³ and partially up to 5 years⁶⁴ without any intervening rehearsals. In fact even after 5 years they retain the ability to quickly re-acquire the skill.⁶⁴ Although the retention of fine motor skills might be different from that of locomotor skills, there is evidence older adults can display similar adaptability⁶⁵ and retention (from our preliminary study) as the young, with a strong likelihood of future fall prevention as well (unpublished data). Further transfer of such acquired motor skills to the opposite limb⁶⁶ and other environmental contexts has also been demonstrated in the young. In spite of the known deterioration in other sensorimotor and cognitive processes with human aging, evidence is emerging revealing the components of motor adaptation and memory that could be preserved and remain intact in the

presence of these aging process and that could be exploited to reduce falls incidence. Hence, such a relatively simple approach of repeated slip exposure can potentially have a lasting practical impact.

Finally, because slip-related falls can cause serious injuries even among healthy, active young adults, the acquisition and retention of fall-resisting skills as proposed in the present study can benefit these people. Certainly, this paradigm to prevent future falls can be particularly attractive to older adult population who are especially prone to having bone mass loss and vulnerable to fracture. At the very least, our findings derived from healthy young adults have provided a strong evidence-based platform and sound rationale to extend such investigation to other populations.

Study Limitations

Though the findings from the study are very promising, the findings may have been impacted by the small sample size. Due to the chance there could be a type I error (rejecting the hypothesis when it is true), results should indeed be considered preliminary and be interpreted and extrapolated with caution. As the statistical power could have been compromised by the small sample size in each group, corrections for multiple comparisons were not performed, so as not to further increase chances of a type II error. Our analysis indicated that a sample size of 20 subjects in each group would indeed result in significant difference at the corrected significance level of .02 with at least a power of .80 between the low-intensity, low-frequency group, and the high-intensity, low-frequency and the low-intensity, high-frequency groups on each of the outcome variables at the 4-month retest. However, in concurrence with our results, the same larger sample size would still fail to yield significant differences between the high-intensity groups with and without ancillary training and between these 2 groups and the low intensity group with ancillary training.

CONCLUSIONS

We propose that a practice schedule consisting of a single training session incorporating, principles of blocked and random practice, and overlearning, could be applied to the healthy younger and community dwelling older adults to induce longer-term retainable effects for prevention of slip-related falls. However, a single slip exposure could have greater appeal to those frail individuals who have limited tolerance or inability to withstand intense training consisting of lengthy session duration. For these individuals we propose that, the single-slip training paradigm can still be effective, when combined with frequent ancillary sessions. We conclude that further research is required to determine whether this type of training actually leads to fewer slip related falls in older adults and that the final choice of the training protocol in this population would depend on the balance of patients/clients' tolerance to repeated slips and the costs of conducting frequent ancillary sessions.

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List of Abbreviations

ANOVA, analysis of variance; BOS, base of support; COM, center of mass; CNS, central nervous system.

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Fig 1.

Shown is a schematic diagram of the experimental set-up with the approximate position of the subject at touchdown of the training (right limb). The unfilled circles indicate positions of passive-reflective markers on the body segments and movable platform. The solid (right side) and dotted (left side) gray lines joining the markers represent the body-segment links used to calculate the whole body center of mass. The I-beam and safety harness system are much higher than shown (9m above the ground). The I-beam extends the length of the 7m walkway 49. The low-friction, nonmotorized moveable top plates (right and left) are mounted on a frame with linear bearings. These devices were locked and embedded in a 7-m walkway and made less apparent by the stationary decoy platforms. Once released, the right moveable platform was free to slide on along the sliding track on the linear bearings. The left plate remained locked and served as a decoy.

Fig 2.

The instantaneous gait stability for an instantaneous COM state (diamond) is the shortest distance (double-headed arrow) between the boundary and the COM state. The COM state consists of the anteroposterior COM position and its velocity relative to the BOS ($X_{COM/BOS}$, $\dot{X}_{COM/BOS}$ respectively). The thick black line represents the boundary for backward loss of balance. The $X_{COM/BOS}$, $\dot{X}_{COM/BOS}$ are normalized to foot length and $\sqrt{g \times h}$, respectively, where g is acceleration due to gravity, and h is the body height.

Fig 3.

Incidence of backward balance loss in percentage (%), demonstrated on the first slip of the initial session (Initial) and the 4-month retest slip (4-mo) for the 4 participating groups: High-intensity, high-frequency (HI_HF, closed circles); high-intensity, low-frequency (high-intensity, low-frequency, open circles); low-intensity, high-frequency (LI_HF; closed square); and low-intensity, low-frequency (LI_LF, open squares). * indicates a significant level of $P < 0.05$ for the independent and paired t tests performed. The exact values for $P < 0.10$ have been reported as well for these comparisons.

Fig 4.

Means and SDs of (a) preslip stability, (b) postsip stability, and (c) hip height on the first slip of the initial session (initial) and the 4-month retest slip (4-month) for the 4 participating groups: high-intensity, high-frequency (HI_HF, closed circles); high-intensity, low-frequency (HI_LF, open circles); low-intensity, high-frequency (LI_HF; closed square); and low-intensity, low-frequency (LI_LF, open squares). NOTE: preslip stability was obtained at instant of preslip touchdown of the slipping (right) limb. Postsip stability and hip height were obtained at the instant of postsip liftoff of the contralateral (left) limb. Hip height was normalized to body height (bh). More positive values of stability indicate greater stability. * indicates a significant

level of $P < .05$ for the independent and paired t tests performed. The exact values for $P < .10$ have been reported as well for these comparisons.