Can treadmill-slip perturbation training reduce immediate risk of over-ground-slip induced fall among community-dwelling older adults?

Yiru Wang [a,b], Tanvi Bhatt [a], Xuan Liu [d], Shuaijie Wang [a], Anna Lee [a,b], Edward Wang [c], Yi-Chung (Clive) Pai [a,*]

[a] Department of Physical Therapy, University of Illinois at Chicago, Chicago, IL, USA
[b] PhD Program in Rehabilitation Science, College of Applied Health and Science, University of Illinois at Chicago, Chicago, IL, USA
[c] Department of Biomedical and Health Information Sciences, College of Applied Health and Science, University of Illinois at Chicago, Chicago, IL, USA
[d] Human Performance and Engineering Research, Kessler Foundation, West Orange, NJ, USA

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ABSTRACT

The purpose of this study was to determine any potential falls-resistance benefits that might arise from treadmill-slip-perturbation training. One hundred sixty-six healthy community-dwelling older adults were randomly assigned to either the treadmill-slip-training group (Tt) or the treadmill-control group (Tc). Tt received 40 slip-like perturbations during treadmill walking. Tc received unperturbed treadmill walking for 30 min. Following their treadmill session, both groups were exposed to a novel slip during over-ground walking. Their responses to this novel slip were also compared to previously collected data from participants who received either over-ground-slip training (Ot) with 24 slips or over-ground walking (Oc) with no training before experiencing their novel over-ground slip. Fall rates and both proactive (pre-slip) and reactive (post-slip) stability were assessed and compared for the novel over-ground slip in groups Tt, Tc, and Oc, as well as for the 24th slip in Ot. Results showed Tt had fewer falls than Tc (9.6% versus 43.8%, $p < 0.001$) but more falls than Ot (9.6% versus 0%, $p < 0.001$). Tt also had greater proactive and reactive stability than Tc (Tt > Tc, $p < 0.01$), however, Tt's stabilities were lower than those of Ot ($p < 0.01$). There was no difference in fall-rate or reactive stability between Tc and Oc, though treadmill walking did improve the proactive stability control of the latter. While the treadmill-slip-training protocol could immediately reduce the numbers of falls from a novel laboratory-reproduced slip, such improvements were far less than that from the motor adaptation to the over-ground-slip-training protocol.

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1. Introduction

Approximately 30% of community-dwelling older adults over 65 years old fall annually (Prudham and Evans, 1981), and these instances may cause mortality and morbidity (Dellinger and Stevens, 2006). Slip-related falls in the elderly comprise 40% of outdoor falls and can result in hip fracture or traumatic head injury (Luukinen et al., 2000; Sterling et al., 2001). A perturbation-based-training protocol in which community-dwelling older adults were exposed to repeated slips on an instrumented over-ground walkway could immediately reduce incidences of laboratory-reproduced falls (Yang and Pai, 2013). This task-specific training involves practicing motor skills involved in avoiding a fall after experiencing a backward loss of balance with a backward recovery

step and demonstrates greater specificity for fall reduction. Specifically, when comparing daily-living falls over a 12-month follow-up period, the training group was seen to experience less than half the number experienced by the control group (Pai, Bhatt, et al., 2014).

The use of a long instrumented-walkway with a complicated setup is limited in clinical and community settings. Thus, a commercially available treadmill could be an option for clinical translation because treadmills are designed to deliver similar over-ground-slip-like perturbations which induce a backward recovery step (Yang et al., 2013). Several studies have applied instrumented treadmills to deliver external postural disturbances during standing, and these reported an improvement in dynamic reactive balance control (Patel and Bhatt, 2015; Patel and Bhatt, 2018; Yang et al., 2018). Yet, a single treadmill-stance-slip perturbation training session with eight slips indicated an insufficient generalization effect to reduce over-ground-slip induced falls (Yang et al., 2018).

It is speculated that recovery from a stance-slip may differ from a gait-slip. Studies which have implemented treadmill-gait-slip perturbation training have mainly focused on clinical performance-based outcome measures, examining predominantly volitional balance and gait control (i.e., one-leg standing time (Shimada et al., 2004), voluntary step execution times (Kurz et al., 2016), and stride variability (Madehkhaksar et al., 2018)). However, fall outcome was not directly assessed in these studies, and outcome measures used might not provide an accurate assessment of improvements in reactive balance control, which is a critical consideration for preventing environmental falls while walking. Recent studies reported the ability of young adults to partially retain acquired treadmill-gait-slip training effects to reduce laboratory re-produced "real-life like" over-ground slips (Lee et al., 2016; Liu et al., 2016; Yang et al., 2013). Previous studies have also demonstrated that, while age-induced deficits in recovery response to a novel perturbation do predispose older individuals to a higher fall risk (Lin et al., 2002), aging does not affect older adults' ability to acquire fall-resisting skills through adaptation to repeated-over-ground slip exposure (Pai et al., 2010). However, it remains unknown whether treadmill-gait-slip training can be effective to reduce older adults' rate of falls immediately post-training.

The purpose of this study was to determine any potential falls-resistance benefits that might arise from treadmill-slip perturbation training. The main aim (Aim 1) was to compare post-training over-ground slip-recovery outcomes between older adults who received treadmill-slip-perturbation training (Tt) and those who received only treadmill-walking (Tc). We hypothesized that Tt would experience fewer falls than Tc and that improved recovery outcomes would stem from improved proactive and reactive dynamic stability control upon encountering a novel over-ground slip while walking. Secondary analyses were conducted to further compare post-training over-ground-slip recovery outcomes between Tt and individuals specifically receiving over-ground-slip training (Ot) (Aim 2), as well as between those who received a treadmill-walking intervention (Tc) and individuals receiving only over-ground walking (Oc) (Aim 3). Specifically, we hypothesized that Ot would show greater proactive and reactive dynamic stability than Tt upon exposure to a novel over-ground slip (Yang et al., 2013), hence demonstrating fewer falls. In addition, we expected there to be no difference in the rate of falls between Tc and Oc. The data for Ot and Oc was previously collected (Pai, Bhatt, et al., 2014).

2. Methods

2.1. Participants

One hundred sixty-six healthy, community-dwelling older adults (≥65 years) were initially screened to pass a cognition test (>25 on the Folstein Mini Mental Status Exam) (Folstein et al., 1975), a calcaneal ultrasound screening (T score > −1.5) (Thompson et al., 1998), and a mobility test (Timed-Up-Go or TUG score < 13.5 s) (Podsiadlo and Richardson, 1991). Exclusion criteria were self-reported recently diagnosed neurological, musculoskeletal, or other systemic disorders that would affect subjects' postural control. One hundred and forty-six of the individuals screened qualified and were randomized to either the treadmill-slip-training group (Tt, N = 73) or the treadmill-control group (Tc, N = 73) (Fig. 1). Randomization was according to a random number (either 0 or 1) generated by Excel "RAND" function. All participants provided written informed consent and this study was approved by the Institutional Review Board in the University of Illinois at Chicago.

2.2. Study design and protocol

The study first adopted a two-arm, randomized controlled design (RCT) to compare Tt with Tc (Fig. 1). Participants had no knowledge whether they were assigned to Tt or Tc until they completed the entire experiment protocol and investigators who performed the post-training over-ground-slip test were also blinded to participants' group assignment in the treadmill session. This trial was registered under the Clinical Trial Registry, NCT02126488.

Tt and Tc walked ~5–10 trials on the walkway at their self-selected speed before then moving on to the treadmill session. Tt received 40 (±0.4) treadmill-slips induced by the ActiveStep treadmill (Simbex, Lebanon, NH) for 30 min (Fig. 2a and 3). Each slip on the treadmill began with 1.3–2 s ramping-up duration followed by three to five steps of walking on a backward-moving belt at participants' self-selected most comfortable speed from the preset options (−0.6 m/s, −0.8 m/s, −1.0 m/s, or −1.2 m/s, with negative signs indicating the moving direction of the treadmill belt was opposite to the direction of participants' COM). To select the preset speed, participants in Tt were asked to walk on the treadmill at −0.8 m/s for 30 s and then were asked whether the speed they had received was their most comfortable speed. They chose whether to increase the walking speed (−1.0 m/s or −1.2 m/s) or to decrease (−0.6 m/s). Once they've reached their most comfortable walking speed, they would receive another 30 s of walking. Subjects in Tt would receive 1.5–2 min of walking to habituate to the treadmill. The belt speed would suddenly reverse directions (accelerating forward) 40 ms after foot strike to cause a forward displacement of participants' base of support (BOS) relative to their center of mass (COM), just as a slip does during over-ground walking. To maximize each participant's potential, the 40 slips were provided over eleven blocks and the perturbation intensity underwent adjustments based on their ability to tolerate it. At each block, the same intensity level would repeat two to four times (Fig. 4a). The intensity of each perturbation profile (P1-P5) was determined by the acceleration of the belt (either 5 or 6 m/s^2) and the duration of its application (ranging from 0.2 to 0.45 s at 5 m/s^2 or 0.3–0.55 s at 6 m/s^2) (Fig. 4b). The slip distance received by participants ranged from 0.1 to 0.51 m at an acceleration of 5 m/s^2 and from 0.27 to 0.91 m at an acceleration of 6 m/s^2. The training profiles were also reported previously (Lee et al., 2018). Tc received only treadmill walking for 30 min. After their treadmill session, both Tt and Tc were immediately transitioned to the over-ground walkway and performed ~5–10 trials of walking at their self-selected speed (equaled to ~2–3 min) before receiving a novel over-ground slip (Figs. 2b and 3). The slip recovery outcomes post-training for the novel over-ground slip were compared between Tt and Tc to test Aim 1.

In addition, post-training outcomes for older adults who received either over-ground-slip training (Ot, N = 109) or an over-ground-control protocol (Oc, N = 103) from a previously collected data set (Pai, Bhatt, et al., 2014; Pai, Yang, et al., 2014) were included as secondary analysis. Ot received ~10 regular walking trials followed by over-ground-slip training consisting of 24 slips induced in a "block and random" manner on a 7-meter walkway, in which the final (24th) slip was used to analyze the post-training effects (Pai, Bhatt, et al., 2014). Oc received only one novel over-ground slip after 10 regular walking trials on the same walkway (Fig. 2b). Slip recovery outcomes were compared between the 24th slip in Ot and the novel slip in Tt to test Aim 2 and between novel over-ground slips in Oc and in Tc to test Aim 3.

Instructions given to participants in each group were identical being: "A slip may or may not occur and try to recover and keep walking forward." All procedures for the four groups occurred over the course of a single laboratory visit and the adherence rate to the
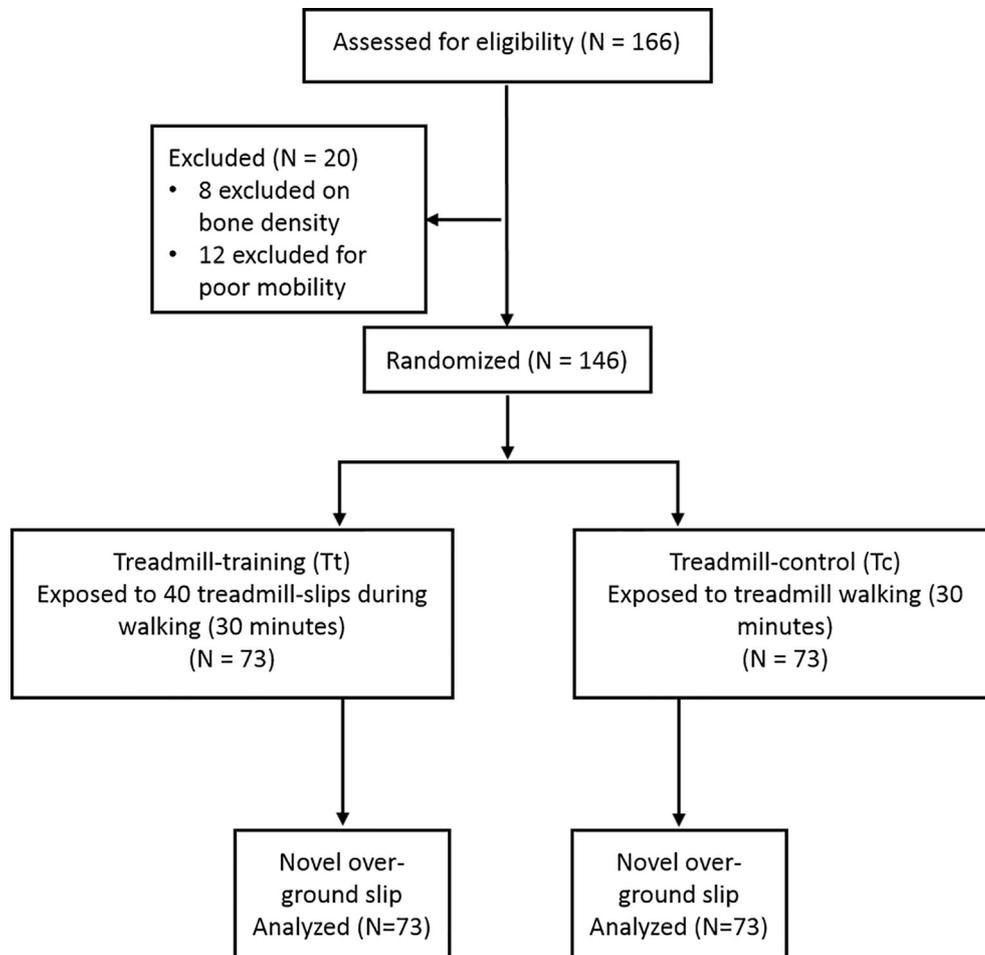
Fig. 1. Flowchart of the number of participants. One hundred and sixty-six community-dwelling older adults were initially screened. One hundred and forty-six of them qualified and were randomized into two groups: the treadmill-slip perturbation training group (Tt, N = 73) or the treadmill-control group (Tc, N = 73).
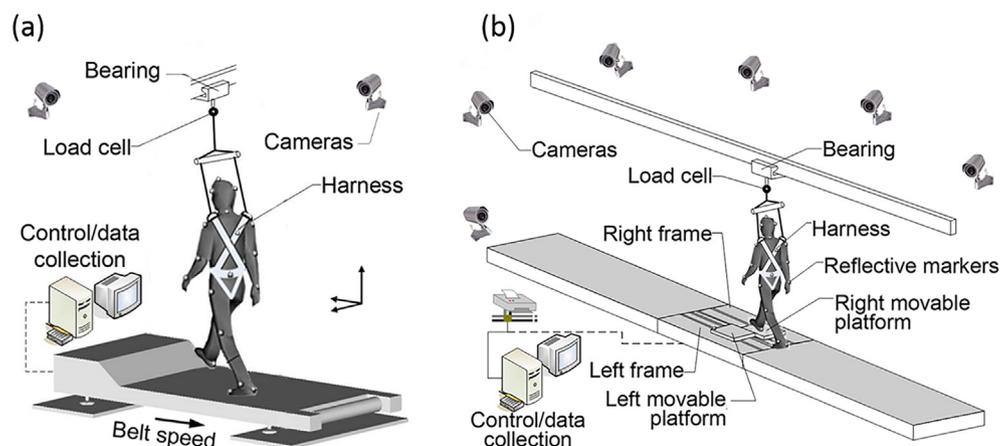

Fig. 2. (a) The computer-programmed treadmill (ActiveStep, Simbex, Lebanon, NH) used for treadmill-slip perturbation training and treadmill walking. (b) The 7-meter walkway with imbedded low-friction movable platforms for inducing over-ground slips and over-ground walking. Beneath the surface, the low-friction bearings of both platform were mounted on top of the low-friction aluminum tracks, resting on four force plates (AMTI, Newton, MA) to record the ground reaction force which were used to control the release of the platforms to provide the over-ground slip. The movable platforms were firmly locked during regular (unperturbed) walking and unlocked electronic-mechanically without the subjects' awareness only in the slip trial at the instant of their right heel strike on the right platform. Once released, the right platform could slide forward freely up to 0.9 m which was comparable to the maximum slip distance in the treadmill-slips. The left movable platform was constructed the same and operated in a similar manner. Participants were protected by a safety harness connected through a loadcell (Transcell Technology Inc., Buffalo Grove, IL) to a low-friction trolley-and-beam system mounted on the ceiling above the treadmill and the over-ground walkway during all trials. Kinematic data from all of the trials was recorded by an eight-camera motion capture system (MAC., Santa Rosa, CA and Qualysis., Gothenburg, Sweden). Motion data was synchronized with the force plates and the loadcell data.
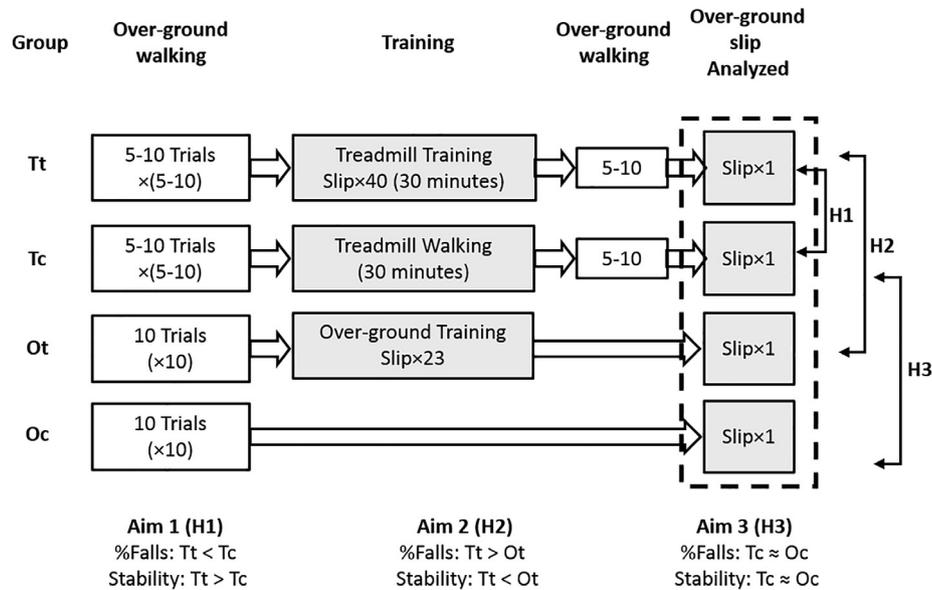
Fig. 3. Schematics of study design. Two treadmill groups, the treadmill-slip perturbation training group (Tt) and the treadmill-control group (Tc) underwent five to ten trials of regular (unperturbed) walking on the 7-meter over-ground walkway. Group Tt then received 40 "slip-like" disturbances on the ActiveStep treadmill system as training which approximated 30 min in the duration. Group Tc received 30 min walking on the treadmill without perturbation at their selected speed. After the treadmill session, both treadmill groups immediately went back to the same walkway for five to ten unperturbed walking trials and then received their novel, over-ground slip as the post-training test. Two over-ground groups: over-ground-slip-training group (Ot) and over-ground-control group (Oc) took approximately ten regular (unperturbed) baseline walking trials on the same 7-meter walkway. Group Ot then received a total of 24 over-ground slips, in which, the final (24th) slip represented the post training trial. Group Oc received one novel, over-ground slip after the baseline walking trials. The results were compared (square in dashed line) for the novel over-ground slips for the Tt, Tc, and Oc groups, as well as for the 24th slip of the Ot group. Group Tt was compared with group Tc to test hypothesis one (H1). Group Tt was compared with group Ot to test hypothesis two (H2). Group Tc was compared with group Oc to test hypothesis three (H3).

current study session was 100%. Three hundred and fifty-eight participants' data was included in the study analysis at the end point.

2.3. Data collection

Participants from four groups were trained and tested in the same laboratory environment. Over-ground slips were conducted on an identical over-ground walkway with a pair of passively moveable platforms imbedded in the middle (Fig. 2b). Once released, the right platform could slide forward freely up to 0.9 m which was comparable to the maximum slip distance in the treadmill-slip. Four force plates (AMTI., Newton, MA) were beneath the surface to record the ground reaction force (GRF), which, in turn, was used to control the release of platforms to provide over-ground slips (Yang and Pai, 2007). All subjects wore a safety harness connected through a load cell (Transcell Technology Inc., Buffalo Grove, IL) during all trials and no participant was informed where, when, or how a slip would occur during their over-ground walking. Load cell and force plate signals were recorded at 600 Hz and were synchronized with the motion data. Body kinematic data was collected at 120 Hz from 26 retro-reflective markers using an eight-camera motion capture system (MAC., Santa Rosa, CA and Qualisys., Gothenburg, Sweden) and analyzed by a customized MATLAB code. Marker paths were low-pass filtered at marker-specific cut-off frequencies (ranging from 4.5 to 9 Hz) using fourth-order, zero-lag Butterworth filters (Winter, 2009).

2.4. Outcome measures

2.4.1. Slip recovery outcomes

Slip recovery outcomes were classified as a fall, backward loss of balance (BLOB), or full recovery (Recovery). A fall was determined when the harness provided support of more than 30% of a person's body weight (Yang and Pai, 2011). BLOB occurred when a person's recovery (left) foot landed posterior to the slipping (right) heel (Bhatt et al., 2006). Full recovery came in one of two forms, a skateover or a walkover (Strandberg and Lanshammar, 1981). Participants who demonstrated full recovery did not rely on taking a recovery step which lands posterior to the slipping foot.

2.4.2. Dynamic stability control

Center of mass (COM) dynamic stability has proven to be a critical factor for preventing slip-related falls during gait (Yang et al., 2009) and has been applied by many studies to quantify the ability to avoid a fall among varied populations (Bhatt et al., 2006; Pai and Bhatt, 2007; Pai et al., 2010; Pai, Bhatt, et al., 2014; Yang and Pai, 2013). Dynamic stability was reported to outperform a battery of clinical tests (i.e. Berg Balance Scale, Isometric muscle strength) used for fall prediction in the laboratory (Bhatt et al., 2011). A greater stability value reflects one's greater ability to simultaneously control their COM motion state, including both the COM position (more anterior shift) and velocity (faster in the forward direction) relative to the perturbed BOS to avoid a slip-induced fall (Pai and Bhatt, 2007) (relative P_{COM} and relative V_{COM}, respectively). COM position was computed from the kinematic data using known gender-dependent segmental parameter information in a 13-segment representation of the body (de Leva, 1996). COM velocity was obtained as the first numerical differentiation of the COM position. Relative P_{COM} and relative V_{COM} were calculated relative to the rear edge of the BOS (i.e., the right heel) and normalized to a dimensionless unit in the anteroposterior direction by foot length (l_{BOS}) and $\sqrt{g \times bh}$ respectively (gravitational acceleration is represented by g and body height is represented by bh). Dynamic stability was calculated as the shortest distance from the instantaneous COM motion state to the boundary of the feasible stability region for backward balance loss under slip conditions (Yang et al., 2009). COM states and stability measures were
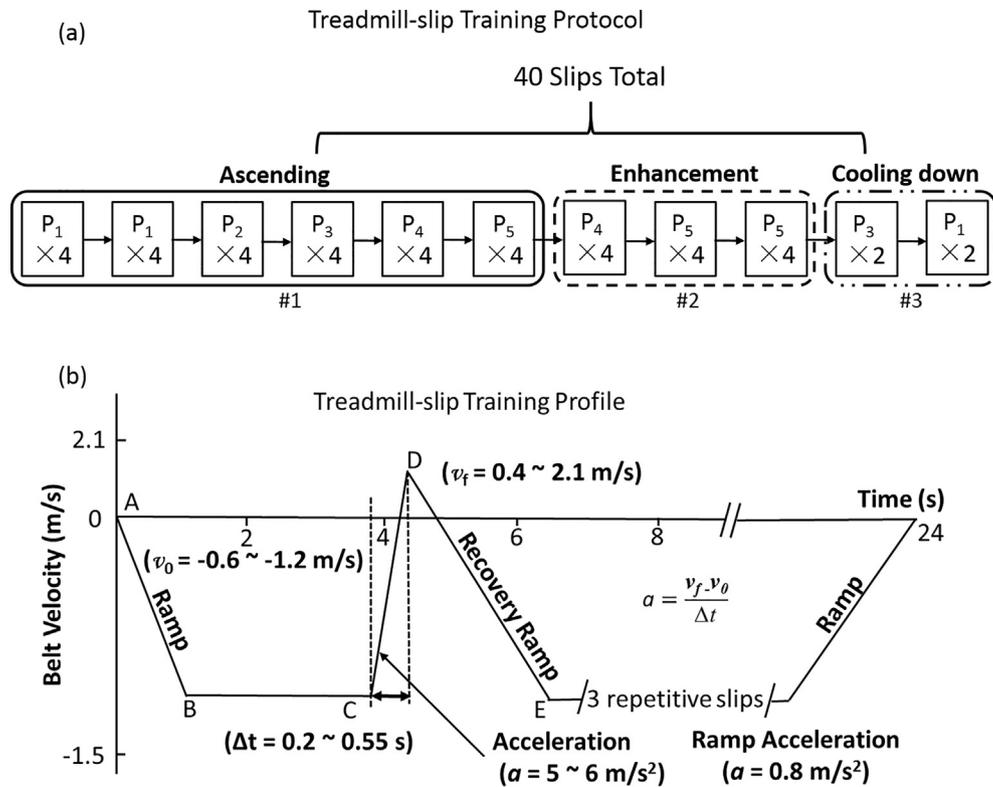
Fig. 4. (a) The total 40 treadmill slips in the treadmill-slip perturbation training protocol were provided over 11 blocks of walking and their perturbation intensity underwent adjustments in three phases. The first phase was a stepwise increase in perturbation intensity (#1, Ascending phase). The second phase was designed to enhance the training effects with repetitive blocks of intensity (#2, Enhancement phase). The third phase was for cooling down (#3, Cooling down phase). P_1-P_5 indicated training profiles with varied perturbation intensity from lowest to highest as the number ascended. (b) The profile of one block of treadmill slips. Each slip on the treadmill began with 1.3–2 s ramping-up duration followed by three to five steps of steady state walking on a backward-moving belt at one of the preset speeds (-0.6 m/s, −0.8 m/s, −1.0 m/s or −1.2 m/s, negative sign indicated that the moving direction of the treadmill belt was opposite to the direction of participants' COM). The preset speeds were selected by the participants as their most comfortable walking speed on the treadmill. Without any warning, the belt speed would abruptly reverse the direction (accelerating forward) to produce a single "slip-like" perturbation. The perturbation intensity of each training profile was determined by two factors, the acceleration of the belt (at two levels: 5 or 6 m/s²) and the duration of its application (ranged from 0.2 to 0.55 s). After each acceleration, the belt deaccelerated at 0.8 m/s² to the previous steady-state walking speed. The next "slip" occurred following another three to five steps of steady-state walking. There was a total of two or four slips in each block.

extracted at slipping (right) foot touchdown (pre-slip), and then at recovery (trailing) foot liftoff (post-slip), to indicate proactive and reactive control respectively (Bhatt et al., 2006).

To examine proactive adjustments in gait pattern, pre-slip step length was calculated as the difference between the heel marker of the slipping foot (right) and the contralateral foot (left) at touchdown of the slipping foot (Bhatt et al., 2006). Absolute V_{COM} and BOS (slip) velocity were measured at the instant of trailing foot lift off and together these determined relative V_{COM}. Slip velocity is a crucial variable for determining adaptive changes (Bhatt et al., 2012), and slip displacement from touchdown of the slipping limb to lift-off of the contralateral limb was also measured to represent the slip severity (Lockhart et al., 2003).

2.4.3. Statistical analysis

One-way ANOVA was performed to identify any differences in age, height, mass, or baseline performance between the four groups. χ^2 test was applied to compare the gender and history of falls between the four groups. Confounding variables which could emerge from sample demographics (i.e. age, height, mass, gender, TUG, and fall history) were included in further analyses as covariates. Categorical data for slip recovery outcomes was examined by a Kruskal-Wallis H test (0: outcomes of fall, 1: loss of balance, and 2: full recovery) and followed by a post-hoc χ^2 test in which a Bonferroni adjustment was made to reduce Type I error. A multivariate general linear model was applied to continuous data with a Bonferroni adjustment in the post-hoc comparison to examine any main

effects of group, and this was done for the novel over-ground-slip trials for Tt, Tc, Oc, as well as for the 24th slip for Ot with the interventions for the four groups being the independent variable. Continuous variables examined were dynamic gait stability, relative P_{COM} and V_{COM}, step kinematics (pre-slip step length), absolute V_{COM}, and BOS (slip) kinematics (i.e., velocity and displacement). All analyses were performed using SPSS 22 (IBM Corp., Armonk, NY) and a significance level of 0.05 was used.

3. Results

Participants in our groups have comparable ages and one-year pre-test history of falls. Participants' height ($p = 0.025$), body weight ($p = 0.01$), gender ($p = 0.001$), and baseline performance in the TUG test ($p = 0.007$) were slightly different and were included as covariates in the multivariable general linear model (Table 1). Dependent variables were significantly influenced by body mass ($p < 0.001$) and TUG ($p < 0.001$).

3.1. Slip recovery outcomes

Slip recovery outcomes differed significantly across groups [χ^2(3) = 233.002, $p < 0.001$]. Ot illustrated the lowest rate of falls (0%) followed by Tt (9.6%), Tc, (43.8%) and Oc (54.4%). Indeed, half of subjects (53.2%) in Ot fell in their novel slip and the fall rate dropped more than half (12%) in trial 2, and was reduced to below 5% by trial 3 and after. Compared to Tc, Tt had significantly

Table 1
Demographics of the subjects (N = 358) at baseline.

	Groups							
	Tc (N = 73)		Tt (N = 73)		Oc (N = 103)		Ot (N = 109)	
	Mean	(SD)	Mean	(SD)	Mean	(SD)	Mean	(SD)
Demographics								
Age (Years)	72.5	6	72.8	6.2	73.1	5.3	71.7	5.1
Height (m)	1.7	0.1	1.6[c]	0.1	1.6[c]	0.1	1.7	0.1
Mass (kg)	70.2[f]	14.9	70.3[a]	14.3	76.3[a,f]	14.9	75.5	12.6
Gender (Female)	62[d,e]		45[a]		79[a,b]		65[b,e]	
TUG (s)	7.9[e]	1.5	7.6	1.4	7.9[b]	1.7	7.2[b,e]	1.5
Falls in previous 1 year per participant (%)	35.6		46.6		35.9		37.4	

Tc = Treadmill-control group, Tt = Treadmill-slip-training group, Oc = Over-ground-control group, Ot = Over-ground-training group; SD = Standard deviation; TUG: The Timed Up and Go test.
[a] Between Oc and Tt, p < 0.05.
[b] Between Oc and Ot, p < 0.05.
[c] Between Tt and Ot, p < 0.05.
[d] Between Tc and Tt, p < 0.05.
[e] Between Tc and Ot, p < 0.05.
[f] Between Tc and Oc, p < 0.05.

decreased rate of falls and increased likelihood of recovery (χ^2 = 23.27, $p < 0.001$). However, compared to Ot, Tt was still significantly inferior in terms of reducing falls and improving full recovery (χ^2 = 10.87, $p < 0.001$). Treadmill walking (Tc) itself did not reduce the rate of falls nor did it alter the recovery rate in comparison to Oc (χ^2 = 1.435, $p = 0.231$) (Fig. 5).

3.2. Dynamic stability control

Proactive control of stability was significantly different across all groups [main effect: F (3, 346) = 14.543, $p < 0.001$] (Fig. 6a). In comparison to Tc, Tt significantly improved proactive control of stability (Tt > Tc, $p = 0.029$). There was no difference in proactive control of stability between Tt and Ot ($p = 0.765$). Treadmill walking improved proactive control of stability compared to no-training (Tc > Oc, $p = 0.015$). Relative P_{COM} was significantly different across groups [main effect: F (3, 346) = 12.628, $p < 0.001$] (Fig. 6b) while relative V_{COM} remained comparable across all groups [main effect: F (3, 346) = 0.949, $p = 0.642$] (Fig. 6c). There was no difference in pre-slip step length between Tt and Tc, or between Tc and Oc (both $p > 0.05$). Participants in Ot had significantly shorter pre-slip step length than Tt (Tt > Ot, $p = 0.016$) (Table 2).

Reactive control of stability was also different across groups [main effect: F (3, 346) = 127.498, $p < 0.001$] (Fig. 6d). In comparison to Tc, Tt significantly improved reactive control of stability (Tt > Tc, $p < 0.001$). Yet, participants who underwent over-ground-slip training were significantly more stable than those who experienced treadmill-perturbation training (Tt < Ot, $p < 0.001$). However, reactive stability on the over-ground slip for the treadmill-control group was similar to the over-ground-control group (Tc ≈ Oc, $p = 1.000$). Relative P_{COM} position [main effect: F (3, 346) = 72.541, $p < 0.001$] (Fig. 6e) and relative V_{COM} [main effect: F (3, 346) = 106.810, $p < 0.001$] (Fig. 6f) were significantly different across groups. Because absolute V_{COM} remained comparable across all groups [main effect: F (3, 346) = 0.445, $p = 0.569$] (Table 2), faster relative V_{COM} (Tt > Tc, $p = 0.007$) (Fig. 6f) could only be due to a reduction in BOS (slip) velocity (Tt < Tc, $p = 0.015$) (Table 2) and the hence reduced slip severity in terms of BOS displacement (Tt < Tc, $p < 0.001$) (Table 2). Both treadmill-slip and over-ground-slip trainings yielded greater improvement in reactive stability control compared to proactive stability control (Tt – Oc: 0.17 for reactive versus 0.07 for proactive; Ot – Oc: 0.39 for reactive versus 0.04 for proactive) (Table 2).
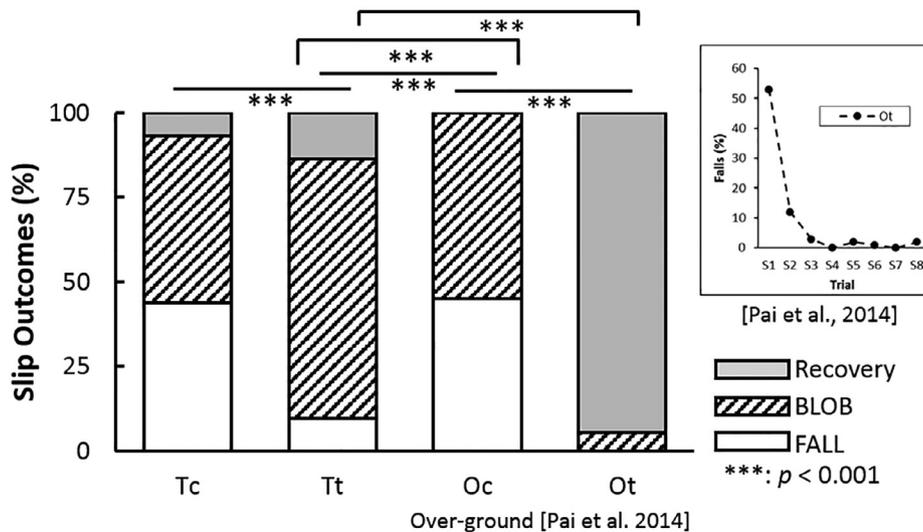

Fig. 5. Slip recovery outcomes and their percentages of falls (FALL, unfilled bar), backward loss of balance (BLOB, hatched lines), and full recovery (FULL, light grey) within the four groups. Significant differences were indicated with a solid line (*** = p < 0.001). Shown in the sub-plot at the right corner is the change in the incidence of falls (S1 through S8) in over-ground-slip-training group (Ot: over-ground-slip-training group).
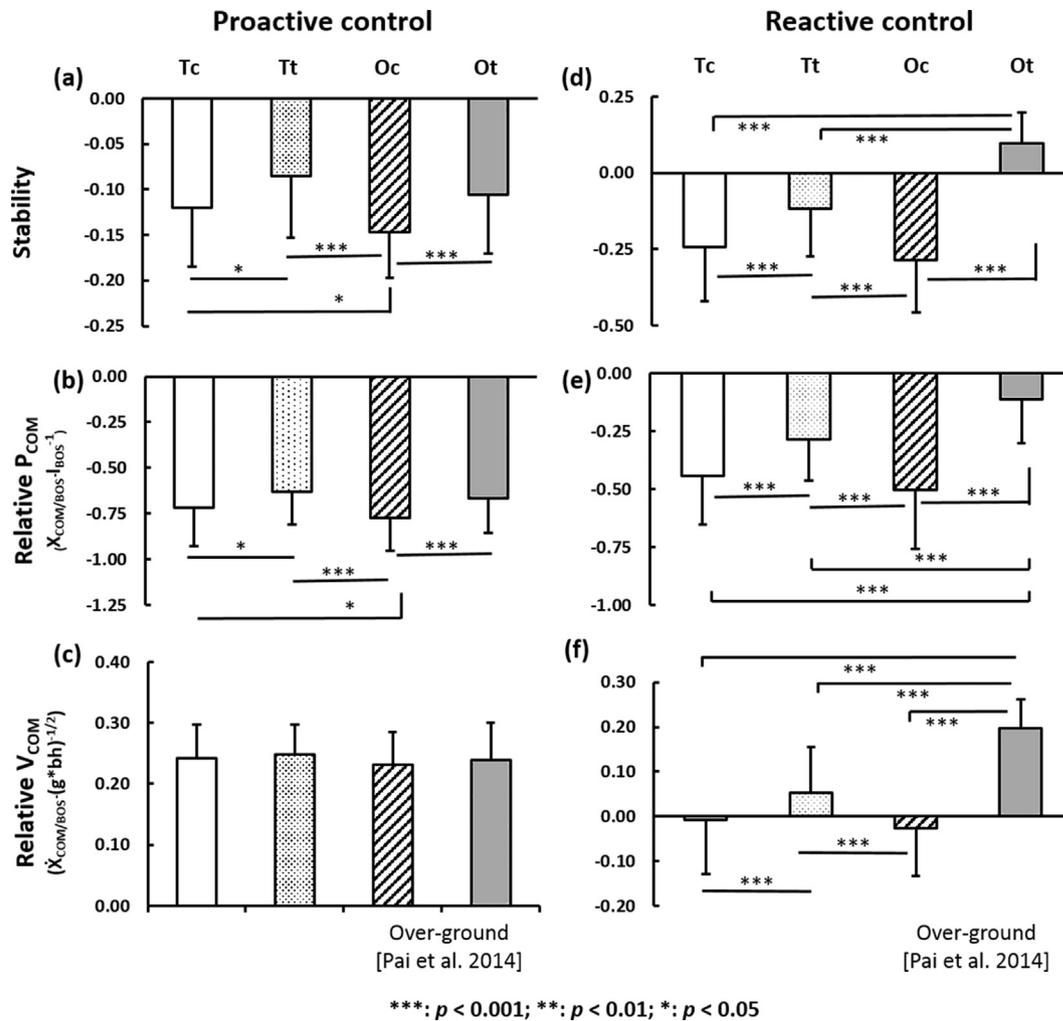
Fig. 6. Dynamic stability within four groups. Proactive control (at the instant of slipping limb touch down) (a–c): (a) proactive stability; (b) COM position relative to the base of support (BOS) (relative P_{COM}); (c) COM velocity relative to the BOS (relative V_{COM}). Reactive control (at the instant of trailing limb lift-off) (d–f): (d) reactive stability; (e) relative P_{COM}; and (f) relative V_{COM}. Both the relative P_{COM} and relative V_{COM} were relative to the rear edge of the base of support (BOS) and normalized by foot length (l_{BOS}) and $\sqrt{g \times bh}$ respectively (gravitational acceleration is represented by g and body height is represented by bh). *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

4. Discussion

While results from the present study revealed that the treadmill-slip-training protocol could improve older adults' resistance to falls, such improvements were far inferior to those gained through motor adaptation to repeated over-ground-slip training. Treadmill walking, though also showing some positive effects on the proactive control of over-ground walking stability, alone was not sufficient to reduce fall-risk immediately following training.

Current findings supported our first hypothesis that, similar to studies on over-ground-slip adaptation in both young and older adults (Bhatt et al., 2006; Pai et al., 2010), improvements in proactive stability were primarily due to an anterior shift in P_{COM} relative to the BOS, but not due to any changes in the relative V_{COM}. Without experiencing the over-ground slip, Tt and Tc did not adopt a shorter pre-slip step length than those who experienced over-ground slips (Ot). Therefore, anterior shifts in P_{COM} might be attributed to other joint kinematics such as a more flexed knee angle or trunk angle. Limited changes in the relative V_{COM} could have resulted from the instructional constraint imposed on participants to continue walking at their natural daily walking speed during over-ground walking. Further, similar to that seen in treadmill-slip-training in young adults, the improvement in reactive control of stability was far greater than for proactive control (Liu et al.,

2016). Older adults' adaptive changes in reactive stability were achieved by both an anterior shift in P_{COM} and an increase in forward V_{COM} relative to the BOS.

Interestingly, and somewhat unexpectedly, the results indicated that treadmill walking alone was able to improve proactive stability control in older participants, and this was caused by an anterior shift in their COM (Fig. 6a). Such a change may be induced by a "cautious gait" (adopting a more forward leaning posture) pattern acquired during the period of treadmill walking, as previously reported (Yang and King, 2016). This improvement in proactive stability control accounted for the fact that 6.8% of participants could still fully recover from a novel over-ground slip after treadmill walking, which was not seen after over-ground walking in Oc (Fig. 5). Yet, treadmill walking was insufficient to improve reactive stability control or reduce the rate of falls.

Contrasting the results of perturbation training with volitional exercises, such as treadmill walking without perturbation (as in the current study), it appears that perturbation training could be superior in inducing significant changes in reactive control of stability. This could be a key distinction between volitional exercises (Jung et al., 2015; Rubenstein and Josephson, 2006; Shumway-Cook et al., 2007) and perturbation training in which disturbances occur without a person's direct knowledge and movement errors are generated (Scheidt et al., 2001). Sensing such errors is essential

Table 2

Summary of p values for all statistical analysis on the slip recovery outcomes, the proactive and reactive dynamic stability, pre-step length, absolute center of mass (COM) velocity, base of support (BOS) velocity at recovery foot lift off, and BOS displacement from slipping foot touch down to recovery foot lift off.

	Groups								p value
	Tc (N = 73)		Tt (N = 73)		Oc (N = 103)		Ot (N = 109)		
	Mean	(SD)	Mean	(SD)	Mean	(SD)	Mean	(SD)	
Slip recovery outcomes (%)									
Fall	44[d,e]		10[c]		54[a,b]		0		<0.001
Backward balance loss	49[d,e]		77[c]		46[a,b]		6		<0.001
Full recovery	7[d,e]		14[c]		0[a,b]		94		<0.001
Dynamic gait stability									
Proactive stability control at slipping (right) foot touch down									
Stability	−0.12[d,f]	0.06	−0.08[d,f]	0.07	−0.15[b]	0.05	−0.11	0.06	<0.001
Relative P$_{COM}$	−0.72[d,f]	0.21	−0.63[d,f]	0.18	−0.77[b]	0.18	−0.66	0.19	<0.001
Relative V$_{COM}$	0.24	0.05	0.25	0.05	0.23	0.05	0.24	0.06	0.642
Pre-slip step length (m)	0.33[e]	0.06	0.32[c]	0.05	0.32[b]	0.05	0.29	0.10	<0.001
Reactive stability control at recovery (left) foot lift off									
Stability	−0.24[d,e]	0.18	−0.12[a,c]	0.16	−0.29[b]	0.17	0.10	0.10	<0.001
Relative P$_{COM}$	−0.44[d,e]	0.21	−0.28[a,c]	0.18	−0.50[b]	0.25	−0.11	0.19	<0.001
Relative V$_{COM}$	−0.01[d,e]	0.12	.05[a,c]	−0.10	−0.03[b]	−0.11	0.20	0.07	<0.001
Absolute V$_{COM}$ (m/s)	1.09	0.25	1.12	0.27	1.04	0.29	1.09	0.27	0.495
Base of support (slip) velocity (m/s)	1.12	0.44	0.90	0.44	1.15	0.49	0.29	0.25	<0.001
Slip severity									
Base of support (slip) displacement from slipping foot touch down to recovery foot lift off (m)									
	0.09[d,e]	0.05	0.07[a,c]	0.04	0.12[b]	0.16	0.03	0.03	<0.001

Tc = Treadmill-control group, Tt = Treadmill-slip-training group, Oc = Over-ground-control group, Ot = Over-ground-training group; SD = Standard deviation; TUG: The Timed Up and Go test.

Two places past the decimal were given for all the variables except for slip recovery outcomes which were rounded to two digits.

[a] Between Oc and Tt, $p < 0.05$.
[b] Between Oc and Ot, $p < 0.05$.
[c] Between Tt and Ot, $p < 0.05$.
[d] Between Tc and Tt, $p < 0.05$.
[e] Between Tc and Ot, $p < 0.05$.
[f] Between Tc and Oc, $p < 0.05$.

for the CNS to recalibrate its internal representation of the stability limits (Blakemore et al., 1998; Shadmehr and Mussaivaldi, 1994) and update the motor commands that can partially or fully correct the errors when a similar disturbance reappears (Albert and Shadmehr, 2016). Given that generalization of acquired adaptation effects was evident within a single session, current findings could be explained by the CNS' error-driven recalibration of stability limits rather than by prospects of improved muscle strength, joint flexibility, or newly acquired motor skills (i.e., from Tai-Chi), all of which are induced typically after long term practice (Buchner et al., 1997; Rubenstein et al., 2000; Wolf et al., 2003).

Current results also lend support to our second hypothesis that the treadmill-slip-training was significantly inferior to the over-ground-slip training for preventing falls. Although evidence indicates that similarity between the training and test episode could yield greater generalization (Shadmehr, 2004), which was further confirmed by Ot's better performance than Tt in this study, current findings indicate that a positive generalization effect from a trained to an untrained context is possible if there is a common motor skill practiced to achieve the same task goal, in this case the prevention of a slip-induced fall. In addition, all over-ground slips occurred under the right side (limb), however, each limb experienced about half of the total treadmill slips induced (Lee et al., 2016). Previous studies reported that the CNS could only partially transfer the increased control in stability acquired through repeated right limb slip training to the opposite limb (Bhatt and Pai, 2008). Therefore, participants who received more slips on the left side would have limited improvements in stability control compared with those who received more slips on the right side. Moreover, the treadmill-belt speed could not be actively controlled by the participant. In contrast, the practice of active individual control of the

GRF beneath each foot during the over-ground-slip training allowed participants to actively slow down or reverse BOS velocity to increase forward COM velocity relative to the BOS, hence improving stability as well as reducing slip distance.

The limitations of the study included that the older adults studied were relatively healthy and might not be representative of the population of older adults more likely to fall. Nonetheless, there is still a high incidence of environmental-condition-related falls reported in such a healthy community-dwelling older adult population (Prudham and Evans, 1981). Protocol-wise, the current study adopted a 40-slip treadmill training paradigm, aimed at further maximizing the retention of the training effect in which the repetition of slips deviated from the over-ground-slip training (24 slips). In addition, without giving any familiarity over-ground-slip trials to subjects in control groups (Tc and Oc) and subjects in treadmill training group (Tt), the significant performance improvements induced in the over-ground-slip training group (Ot) could be attributed due to task familiarity. Further, a future study design exposing participants to a small magnitude of over-ground perturbation for familiarization to all groups could better capture and differentiate the acquired (training-induced) fall-resistance skills between. Further, it remains unknown whether increasing the training threat dosage (intensity) or the practice dosage (repetition) of current treadmill-slip-training protocols would yield better generalization to the over-ground slip. Finally, the long-term effect of treadmill training is unknown, however, a previous study reported that frail older adults who received a 6-month treadmill perturbation training had a 21% lower rate of community falls compared with those who received conventional exercise training (Shimada et al., 2004), suggesting that treadmill training could be a useful method for preventing community falls.

Moreover, a single session Ot was able to reduce community falls by 50% 1-year post-training (Pai, Bhatt, et al., 2014).

In summary, while following a single-session treadmill-slip-training protocol could immediately reduce the numbers of falls from a novel laboratory-reproduced slip, such improvements were far less than that from the motor adaptation to the over-ground-slip-training protocol among healthy community-dwelling older adults. The impacts of generalization and retention of training effects on reducing falls in everyday living need to be further studied.

Acknowledgements

Conflict of interest

The authors have no conflicts in the manuscript, as noted above.

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