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RESEARCH ARTICLE

Treadmill-gait slip training in community-dwelling older adults: mechanisms of immediate adaptation for a progressive ascending-mixed-intensity protocol

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Abstract
The study purpose was to investigate whether older adults could improve their stability against a backward loss of balance (BLOB) after receiving repeated treadmill slips during walking and to see how such adaptive changes would be affected by practice dosage (combination of slip intensity and the number of slips at each intensity). Twenty-five healthy community-dwelling older adults received forty treadmill slips given over eleven blocks at five intensities (*P*1–*P*1–*P*2–*P*3–*P*4–*P*5–*P*4–*P*5–*P*5–*P*3–*P*1, larger number indicating higher intensity). Center of mass (COM) stability was calculated as the shortest distance of the instantaneous COM position and velocity relative to the base of support (BOS) from a theoretical threshold for BLOB (larger stability value indicated a better stability against BLOB). Stability, step length, and trunk angle were measured before and after slip onset to reflect proactive and reactive control, respectively. The first slips at each intensity block (i.e., *P*1, *P*3, *P*4, and *P*5) were compared with the first slips in the last blocks at those intensities to examine main effects of training dosage (intensity and repetition). Improvements in proactive and reactive stability were more pronounced for receiving more slips at larger intensities than fewer slips at smaller intensities. Older adults only demonstrated partial positive scaling effects to proactively, not reactively, establish a more stable initial COM state. The improved proactive stability was associated with an anterior shift of COM position relative to the BOS, resulting from a shorter pre-slip step length. The improved reactive stability was associated with an anterior shift of COM position, resulting from a larger compensatory step length and a faster COM velocity relative to the BOS. Our findings indicated that treadmill-gait slip perturbations elicited similar proactive and reactive control to that from over-ground slip perturbations, but greater slip intensity and repetition might yield more immediate adaptive improvements.

Keywords Perturbation · Stability · Treadmill · Motor adaptation

Introduction

Over one-third of community-dwelling older adults above 64 years of age fall annually (Prudham and Evans 1981). Slip-related falls among these people comprise 40% of outdoor falls and can result in devastating hip fracture or traumatic head injury (Luukinen et al. 2000; Sterling et al. 2001). Subsequent fear of falling can lead to decreased physical activity, and this can negatively impact individuals' quality of life (Stenhagen et al. 2014). Hence, it is imperative to develop approaches to reduce the risk of slip-related falls among older adults.

Perturbation training, unlike volitional performance-based interventions, is an emerging task-specific training paradigm which comprises unexpected postural disturbances to simulate the accidental nature of falls (Bohm et al. 2015). Recovering from such a disturbance involves rapid and effective reactive execution of whole-body compensatory responses, such as forward or backward stepping. Past literature demonstrated that the pattern of muscle activation (i.e., magnitude of activation, onset of activation, and sequence of activation) seen when recovering from a trip or a slip was different from that seen during execution of volitional steps

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during unperturbed walking or standing (Chambers and Cham 2007; Eng et al. 1994). These findings suggest that the strategy needed to recover from a perturbation is highly task specific and might not be reproduced during movements involving only volitional controlled walking. Specifically, previous studies found that a 16-week lower extremity strength training program failed to significantly reduce trips during over-ground locomotion (Pavol et al. 2002a), and, similarly, an 8-week exercise-based combined balance and strength training intervention did not reduce falls upon exposure to a novel slip induced during over-ground walking (Kim and Lockhart 2010). In contrast, a single short session of treadmill-trip or treadmill-slip training was found to have the potential to reduce trips and slips during over-ground locomotion, respectively (Grabiner et al. 2012; Wang et al. 2018).

Several studies over the past decade have demonstrated the ability of older adults (similar to that of young adults) to acquire, retain, and generalize adaptations to real-life-like slip perturbations (Bierbaum et al. 2010, 2011; Karamanidis et al. 2011; McCrum et al. 2016; Pai et al. 2010; Pavol et al. 2002b; van Hedel and Dietz 2004). Although previous findings have demonstrated aging-induced deficiencies in the magnitude of the response, such as slower reaction time (van den Bogert et al. 2002) and lower peak ankle moment (Martelli et al. 2017; Pijnappels et al. 2005) when recovering from a novel slip or trip, discrepancies in walking speed and muscle strength between the two age groups were found to have a relatively weak contribution to overall recovery response upon exposure to repeated perturbations (Senden et al. 2014). Further, studies found that both young and older adults generated similar motor recovery strategies across trials (Martelli et al. 2017) and demonstrated similar adaptation patterns following repeated perturbation exposure (Bhatt et al. 2006b; Pai et al. 2010; Pavol et al. 2004). For example, repeated slip exposures during a sit-to-stand task led to rapid fall reduction, within 3–5 trials, at similar rates for both age groups (Pai et al. 2010; Pavol et al. 2002b). Similarly, after experiencing a novel over-ground slip, older adults demonstrated proactive adjustments similar to those seen in young subjects, including a shorter step length and a flat-foot landing to bring the center of mass (COM) closer to the base of support (BOS) before the next slip (Pai et al. 2010). These feed-forward adjustments subsequently modified older adults' reactive control to achieve a better dynamic stability against backward balance loss after slip onset by reducing the slipping distance (Bhatt et al. 2006b, 2011a; Pai et al. 2003, 2014; Yang and Pai 2013). Such training-induced, rapid adaptation indicates the central nervous system's ability to adjust future movements to new demands based on previous errors. This error-driven process is inherently important for rehabilitation because of its ability to incorporate complex motor components (muscles and bones) in an instant (Bastian 2008). Moreover, these recent studies demonstrated improved dynamic gait stability through repeated perturbations, despite previously described local variances (i.e., onset of muscle activation) between young and older individuals, reflecting improved global fall-resisting skills against backward loss of balance (Pai and Patton 1997; Yang et al. 2007). Further, it has been reported that the improvements in dynamic stability control acquired by healthy older adults from the over-ground slip training paradigm could be retained for about 12 months, resulting in reduced incidences of laboratory falls (Pai et al. 2010) and falls during daily living (Pai et al. 2014).

However, most studies on older adults as above mentioned were done using a custom-designed over-ground walkway device with a passive moveable platform (Bhatt et al. 2006a, b; 2011b; Pai et al. 2010; Pavol et al. 2004; Yang et al. 2014). Compared with the complex laboratory setting previously used for the over-ground walking slip perturbation paradigm, the commercially available treadmill-slip perturbation system is an emerging technology with the potential for effective training, while also requiring less space for setup and offering precise control of walking speed and perturbation intensities, making it more feasible for clinical and community settings. Therefore, studying treadmill-slip training-induced adaptation and generalization is of great importance. Protocol-wise, the ability of a treadmill-slip device to modulate perturbation intensity trial-by-trial gives researchers greater freedom to investigate how an individual adapts to different slip intensities within one training session to develop an optimal training protocol. This differs from the over-ground slip-perturbation paradigm where several cohorts of participants would be needed to study training-induced effects from different protocols with varied intensities. Nevertheless, adaptive stability control in older adults during treadmill-gait slip perturbation training remains less studied than over-ground slip paradigms. A few studies did report adaptive improvements in stability control during treadmill-stance perturbation training (Kim and Lockhart 2010; Patel and Bhatt 2015); however, the symmetrical bipedal stance slip inherently differs from the asymmetrical gait slip.

Although studies on adaptation to treadmill-gait slips are limited, recent studies did show that both young (Lee et al. 2016; Liu et al. 2016) and healthy older adults (Wang et al. 2018) could potentially generalize the fall-resisting skills acquired from a single session of repeated treadmill-gait slips to reduce falls on a novel slip induced during over-ground walking. In addition to the promising findings of a single session, one shared finding for both young and older adults was that the fall-resisting skills against an over-ground slip which were acquired from treadmill-induced generalization were inferior to those acquired from over-ground adaptation. However, none of the studies mentioned above have reported the within-training adaptive changes in proactive and reactive dynamic stability control. By examining these changes, one could better examine how participants adapt to treadmill-gait slip perturbations to understand why inferior fall-resisting skills were observed for the treadmill paradigm. Therefore, a study which further inspects trial-to-trial adaption during treadmill-gait slip training, instead of only examining pre- and post-treadmill training performance during over-ground slips (Lee et al. 2016; Liu et al. 2016; Wang et al. 2018; Yang et al. 2013), remains novel and necessary to investigate and provide insights into the possible mechanisms of the generalization observed.

Previous studies have demonstrated that the training dosage (perturbation intensity and repetition) could affect training-induced immediate adaptation (McCrum et al. 2016; Patel et al. 2018), generalization (Lee et al. 2016; Liu et al. 2016), and retention (Bhatt and Pai 2009; Bhatt et al. 2006a; Patel and Bhatt 2018). For example, a higher-intensity (acceleration) treadmill training protocol yielded greater transfer to over-ground slips compared to a lower intensity training protocol, with the effects from progressive ascending intensities being second best to the higher-intensity protocol (Liu et al. 2016). Similarly, eight treadmill trips were seen to result in greater retention than a single treadmill trip (König et al. 2019). However, in older adults, beginning training with too high of an intensity, as well providing too many sessions or slips per session, might increase the intolerability and fear of falling, leading to incompliance to the training. Hence, an optimal protocol might begin with progressive ascending intensities as a warm up to increase training tolerability and be followed by a single session of mixed, high-intensity slips to promote compliance and maximize the training-induced generalization and retention effects.

Thus, the purpose of this study was to investigate whether older adults could improve their stability against a backward loss of balance by adapting to repeated treadmill-gait slips. In addition, by designing the protocol in an "ascending-mixed-intensity" manner, the study aimed to determine how such adaptive changes were affected by different practice dosages (combination of slip intensity and numbers of slips at each intensity). We hypothesized that for each intensity level, there would be significant improvements in proactive and reactive dynamic stability from the first exposure to the later post-training exposure, resulting from altered COM motion states, longer reactive compensatory stepping, and improved trunk control. Past literature has reported young adults' ability to demonstrate positive scaling of the compensatory stepping response by modulating step length based on the intensity of the perturbation received (Patel and Bhatt 2015). Such findings indicate the CNS's ability to recalibrate and modulate the motor response to a higher intensity based on sensory information about the perceived threat. Hence, we also postulated that when comparing the novel first exposure of ascending intensities, there would be a significantly greater stability at the higher intensity due to a positive scaling effect.

Methods

Participants

Twenty-five healthy, community-dwelling older adults (age = 70.2 ± 5.9, female = 10) were screened to pass a calcaneal ultrasound screening (T score > − 1.5) (Thompson et al. 1998) to minimize experiment-related risk of fracture, a cognitive test (> 25 on the Folstein Mini Mental Status Exam) (Folstein et al. 1975) to ensure participants' ability to understand and follow directions, and a mobility test (Timed-Up-Go or TUG score < 13.5 s) (Podsiadlo and Richardson 1991) to limit training sessions to 30 min to reduce participant fatigue. Exclusion criteria were recently diagnosed, self-reported neurological, musculoskeletal, or other systematic disorders which could affect participants' postural control. Participants completed the entire training protocol during the course of a single laboratory visit. All participants provided written informed consent and this study was approved by the Institutional Review Board of the University of Illinois at Chicago.

Experiment setup

Participants received 40 slips induced during walking by a computer-controlled treadmill (ActiveStep, Simbex, Lebanon, NH) (Fig. 1a). The belt velocity would suddenly reverse directions (accelerating forward) to cause a forward displacement of participants' BOS relative to their COM, just as a slip does during over-ground walking. Each slip on the treadmill began with 1.3–2 s ramping-up duration followed by 3–5 steps of unperturbed treadmill walking at the 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 the direction of participants' COM). The slip perturbation intensity was determined by the forward belt slip distance together with the slip acceleration and duration (Fig. 1b). Each participant received five levels of intensity ($P1$–$P5$, with larger numbers indicating higher perturbation intensities) each with increased slip distances (Fig. 2). All participants were protected during the entire test session by a full-body safety harness which was attached to a load cell via a pair of shock absorbing ropes and then to a low-friction, ceiling-mounted track.

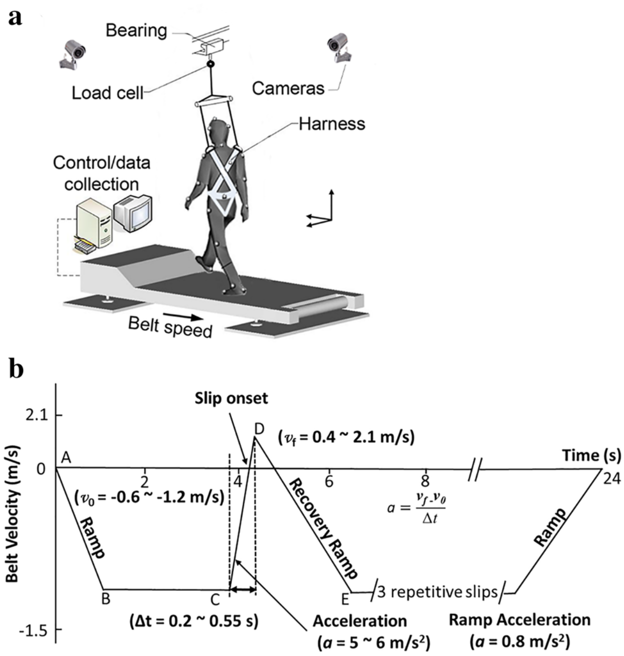

Fig. 1 **a** The computer-programmed treadmill (ActiveStep, Simbex, Lebanon, NH, USA) used for treadmill-slip perturbation training and treadmill walking. **b** The profile of one block of four treadmill slips. Each slip on the treadmill began with 1.3–2 s ramping-up duration followed by 3–5 steps of 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 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/s^2) and the duration of its application (ranged from 0.2 to 0.55 s). After each acceleration, the belt deaccelerated at 0.8 m/s^2 to the previous steady-state walking speed. The next "slip" occurred following another three to five steps of steady-state walking. There were a total of two or four slips in each block

Study protocol

All participants received 2 min of walking on the treadmill without perturbation to habituate to the treadmill walking. They were instructed to catch the moving belt and select the most comfortable speed from four pre-set levels (−0.6, −0.8, −1.0, and −1.2 m/s) at which they could walk normally. Among the 25 participants, two selected the initial speed to be −0.6 m/s, 15 selected the initial speed to be −0.8 m/s, seven selected the initial speed to be −1.0 m/s, and one selected the initial speed to be −1.2 m/s. All participants were then instructed that a slip may or may not occur during the following treadmill walking. They were asked to respond in their natural way (i.e., try not to grab the harness) to recover their balance and prevent themselves from falling.

Forty slips were given over 11 blocks at five intensity levels (*P*1–*P*1–*P*2–*P*3–*P*4–*P*5–*P*4–*P*5–*P*5–*P*3–*P*1) (Fig. 2). The protocol was designed in an "ascending-mixed-intensity" manner in which the ascending-intensity phase served as a warm up session to increase the tolerability of training, as well as to demonstrate substantial training induced generalization (Liu et al. 2016), and the mixed-intensity phase maximized the potential of training-induced effects (Schmidt and Wrisberg 2008). Further, such a protocol was also chosen as it would also allow us to examine adaptation-induced scaling at higher intensities, if present. Each block started with 8–10 unperturbed steps before four consecutive slips were given at the same intensity level. A short break (< 30 s) could be given between blocks based on participants' needs. The training session started with a baseline block of four slips at *P*1 followed by 20 slips given in five intensity blocks (*P*1–*P*5) in the progressive ascending acquisition phase. A mixed-intensity session then followed which comprised blocks of slips at mixed intensity (Fig. 2). Participants had to recover from at least one of the slips (no fall) in each block to proceed to the next intensity level. The slip intensity (belt displacement) in the higher level increased approximately 10–35% from that in its adjacent lower level, and this increment was chosen based on previous studies which reported treadmill training (Grabiner et al. 2012; Lee et al. 2018; Patel and Bhatt 2015) (Table 1). In the current study design, the novel slip at each intensity was compared with the first slip in the last block at that same intensity level to investigate pre- to post-training effects (i.e., $P1_{pre}$ vs $P1_{post}$, $P3_{pre}$ vs $P3_{post}$, $P4_{pre}$ vs $P4_{post}$, and $P5_{pre}$ vs $P5_{post}$) (Fig. 2). In addition, because *P*1 was repeated in three blocks, we also compared the first *P*1 in block 2 ($P1_{mid}$) with $P1_{pre}$ and $P1_{post}$ to examine any possible effect of the small training dosage on slips at low intensity (*P*1). Moreover, $P1_{pre}$, $P3_{pre}$, $P4_{pre}$, and $P5_{pre}$ in the ascending training session were compared to investigate the scaling effects.

Data collection

The actual belt speed and displacement were registered by the ActiveStep treadmill system. Full-body kinematic data from 26 retro-reflective markers placed on participants' bodies were captured using an 8-camera motion-capture system (Qualysis, Gothenburg, Sweden) at 120 Hz. A computer program written in LabView (National Instruments Inc., Austin, TX, USA) was used to synchronize the start of the treadmill belt with the motion recording as well as with the load cell. The timings for two transient events in each gait cycle [pre-slip onset touchdown (PD) and recovery touchdown after slip onset (RD)] were identified from foot kinematics (Zeni et al. 2008) and were confirmed by a pressure-sensing mat equipped beneath the belt which consistently recorded dynamic pressure data under both feet.

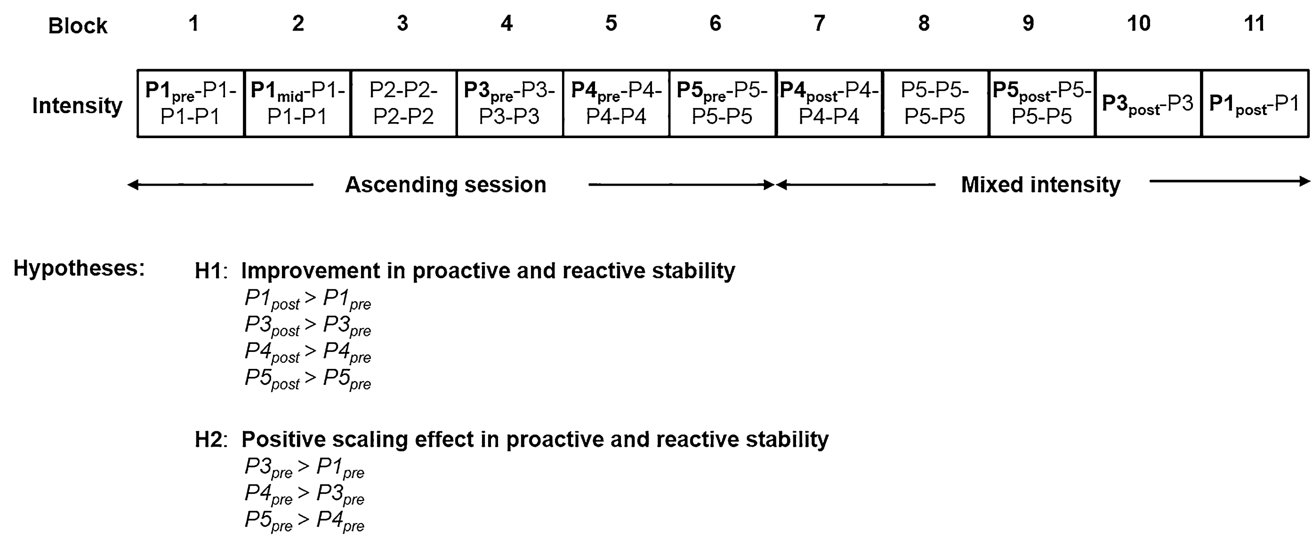

Fig. 2 The "ascending-mixed-intensity" treadmill-slip perturbation training protocol. Forty slips were given over eleven blocks at five intensity levels with a larger number indicating a larger slip intensity. The first nine blocks (blocks 1–9) included four slips in each block and the last two blocks (blocks 10 and 11) included two slips in each block. The bolded trials represented trials of study interests (i.e., $P1_{pre}$ in block 1). Specifically, the first trial of each block (i.e., $P1_{pre}$, $P3_{pre}$, $P4_{pre}$, and $P5_{pre}$) was compared with the first trial of the later block at the same intensity level (i.e., $P1_{post}$, $P3_{post}$, $P4_{post}$, and $P5_{post}$) to test the pre- and post-training effect (H1). In addition, the first trials of each block (i.e., $P1_{pre}$, $P3_{pre}$, $P4_{pre}$, and $P5_{pre}$) were compared to test the scaling effect in the ascending session (H2)

Table 1 Treadmill-slip profiles

Initial belt velocity, acceleration	Slip distance (m)				
	P1	*P2*	*P3*	*P4*	*P5*
1.2 m/s, 6 m/s^2	0.4	0.5	0.6	0.8	0.9
1.0 m/s, 6 m/s^2	0.3	0.4	0.5	0.6	0.8
0.8 m/s, 5 m/s^2	0.2	0.2	0.3	0.4	0.5
0.6 m/s, 5 m/s^2	0.1	0.2	0.2	0.3	0.4

Outcome measures

The body COM kinematics were computed using filtered marker positions based on a 13-segment rigid body with gender-dependent segmental inertial parameters (de Leva 1996). Kinematic variables were computed using custom written algorithms in MATLAB. Before slip onset, the rear of the BOS was taken as the heel marker of the leading foot, and after slip onset, the rear of the BOS was taken as the heel marker of the first recovery landing foot. The BOS velocity was taken as the belt velocity. The two components of the COM motion state (position and velocity) were calculated relative to the rear of the BOS ($P_{COM/BOS}$ and $V_{COM/BOS}$) and were normalized by foot length (l_{BOS}) and $\sqrt{g \times bh}$, respectively, where g is gravitational acceleration and bh is the body height. Stability was calculated as the shortest distance from the COM motion state to the threshold against backward balance loss (BLOB) in which the threshold against BLOB was computed with a mathematical model representing all possible combinations of COM position and velocity satisfying an upright equilibrium without initiating a backward step (Yang et al. 2008). Dynamic stability was calculated at PD and RD to indicate proactive and reactive stability control, respectively. The timing of slip onset (SO) was defined as the instant at which the direction of belt movement started to change (transit point from backward to forward) (Fig. 1b). The slip characteristic was defined as a single-stance slip, if the SO occurred after recovery limb lift-off; or a double-stance slip, if the SO occurred before recovery limb lift-off. The pre-slip onset step length was calculated as the distance between the heel marker of the leading foot at PD and the contralateral foot normalized by the body height. The recovery step length was calculated as the anteroposterior displacement of the stepping limb heel marker from SO to RD (with a more negative value indicating a larger backward recovery step) (Patel and Bhatt 2015). We limited the investigation of stability to the first recovery step because 100% of the first recovery steps were completed before the belt started to reverse direction again (between points *C* and *D*, Fig. 1b), meaning that the braking force generated by the belt would not provide additional impact on dynamic stability (Pai and Iqbal 1999). Furthermore, the number of compensatory steps taken to recover balance was calculated. Individuals were said to have taken two or more compensatory steps when the perturbation required more than one step to recover balance and the second step landed posterior to the first step. Trunk angle was the angle between the trunk segment (defined by a line connecting the midpoint of the shoulders and the midpoint of the hips) and it was collected at PD and RD with more negative values denoting trunk flexion.

Statistical analysis

The Cochran's Q test was applied for testing differences in slip characteristics (single-stance slip versus double-stance slip) between the first slip in each of the eleven blocks. Follow-up pairwise comparison was conducted using the McNemar test. The Friedman test was used to test for differences in recovery steps between the first slip in each of the eleven blocks with the Wilcoxon's signed-rank test used for post hoc comparison. These tests served as preliminary analyses to examine any confounding variables that could be due to the slip characteristics and aimed to investigate the general recovery response (in terms of recovery steps) to perturbation. To test the first hypothesis, which proposed investigating the pre- to post-training effect, as well as the effects of intensity and slip timing, a three-way repeated ANOVA was firstly conducted to test the overall effects of trial (two levels: pre-training and post-training), intensity (four levels: $P1$, $P3$, $P4$, $P5$), and timing (two levels: PD and RD) on dynamic stability (eight trials: $P1_{pre}$, $P1_{post}$, $P3_{pre}$, $P3_{post}$, $P4_{pre}$, $P4_{post}$, $P5_{pre}$, and $P5_{post}$). Simple contrasts were performed to resolve any significant interactions from the three-way repeated ANOVA. To examine the scaling effect, as proposed in the second hypothesis, which could have emerged from the increment in the slip intensity exposure, repeated one-way ANOVAs were then applied across intensities in the ascending session at PD for proactive stability and at RD for reactive stability, respectively. Follow-up pairwise comparisons with Bonferroni adjustments were further applied to compare the pre- to post-training changes in proactive and reactive stability at $P1$, $P3$, $P4$, and $P5$ for hypothesis one, as well as to compare the differences in proactive and reactive stability at $P1$, $P3$, $P4$, and $P5$ in the ascending session for hypothesis two, respectively. In addition, pairwise comparisons were also applied between $P1_{pre}$ and $P1_{mid}$, and between $P1_{mid}$ and $P1_{post}$ to examine any potential training effect of the small training dosage at only intensity $P1$. Linear mixed models were performed between stability and $P_{COM/BOS}$ and $V_{COM/BOS}$ at PD and RD, respectively, to examine the overall influence of the COM variables on stability. To determine the mechanism of stability modulation, linear mixed models were again performed between $P_{COM/BOS}$ and both pre-step length and trunk angle at PD, as well as between $P_{COM/BOS}$ and both recovery step length and trunk angle at RD. Participants' ID (repeated in different trials) was included as a random factor in linear mixed models and trial was inputted as a repeated factor. The significance level for all analyses was set at $p < 0.05$. The analyses were performed using SPSS 22 (IBM Corp, Armonk, NY, USA).

Results

Slip characteristics and compensatory step response

The Cochran's Q test determined that there were no significant differences in slip characteristics across trials [χ^2 (10) = 4.07, $p = 0.907$]. Unlike over-ground slips and treadmill-stance slip perturbations, where slips always occurred during individuals' double stance with both of their feet in contact with the belt, during treadmill walking, about 86% of slips occurred during the single-stance phase and about 14% of slips occurred during the double-stance phase (Table 2). All participants demonstrated at least one backward compensatory stepping response upon sudden forward perturbation, and there was a statistically significant difference in the number of recovery steps across trials (χ^2 (10) = 140.764, $p < 0.001$). The Wilcoxon signed-rank test showed that training did not elicit a statistically significant change in the number of recovery steps at all intensity levels ($P1_{pre}$ vs $P1_{post}$, $P3_{pre}$ vs $P3_{post}$, $P4_{pre}$ vs $P4_{post}$, $P5_{pre}$ vs $P5_{post}$, all $p > 0.05$). However, subjects did take more steps to recover from slips at higher intensity levels compared with slips at lower intensity levels ($P5_{pre} > P4_{pre} > P3_{pre} > P1_{pre}$, all $p < 0.05$).

Improvement from pre- to post-training at varied intensity levels

Overall, subjects had improved stability from pre- to post-training [F (1, 20) = 23.732, $p < 0.001$]. Also, there were statistically significant main effects of slip timing [F (1, 20) = 31.213, $p < 0.001$] and slip intensity [F (3, 60) = 4.801, $p < 0.001$] on stability (Fig. 3). Contrasts were then performed to break down the interaction between training and intensity [F (3, 60) = 8.192, $p < 0.001$] from the three-way ANOVA model by comparing each level of intensity to training outcome measures. These contrasts revealed a significant interaction when comparing $P1$ through

Table 2 Slip characteristics and the number of compensatory recovery steps taken for the first slip in each block

Intensity	$P1$	$P1$	$P2$	$P3$	$P4$	$P5$	$P4$	$P5$	$P5$	$P3$	$P1$
Single-stance slip (%)	84	88	84	92	88	84	80	88	80	92	88
Recovery step (mean#) (SD)	2.4 (0.9)	2.2 (0.9)	2.6 (1.1)	3 (1.1)	3.8 (0.9)	4.5 (1.2)	3.4 (1.1)	4.3 (1.1)	4.3 (1.1)	2.8 (1.1)	2 (0.9)

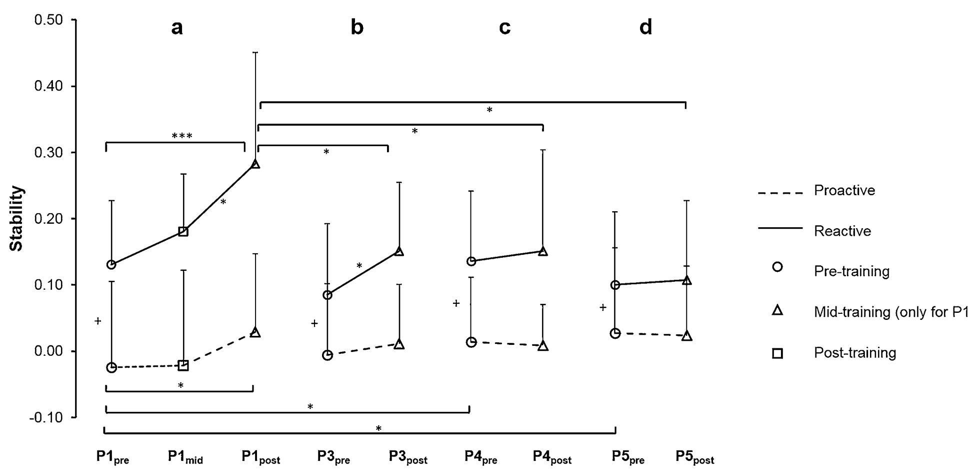

Fig. 3 Proactive and reactive stability control for each trial at the instant of pre-slip touchdown (PD) and post-slip recovery foot touchdown (TD) pre- to post-training. Panel a indicates proactive and reactive stability for *P*1 from pre- to post-training as well as the mid-training trial. Panel b, c, and d indicate proactive and reactive stability for *P*3, *P*4, and *P*5 from pre- to post-training, respectively. $*p<0.05$, $**p<0.01$, and $***p<0.001$. The symbol "+" indicates a significant difference between proactive and reactive stability for *P*1, *P*3, *P*4, and *P*5 at both pre- and post-training

*P*5 to training outcome measures [F (1, 20) = 16.701, $p<0.001$], finding that training-induced improvements in stability control were more pronounced for *P*1. Specifically, pairwise comparisons revealed that reactive stability improved significantly from pre- to post-training for both *P*1 and *P*3 ($P1_{post}$_RD > $P1_{pre}$_RD, $p<0.001$; and $P3_{post}$_RD > $P3_{pre}$_RD, $p=0.004$), but there was no pre- to post-training improvement in reactive stability for *P*4 or *P*5 ($P4_{pre}$_RD = $P4_{post}$_RD and $P5_{pre}$_RD = $P5_{post}$_RD, both $p>0.05$). In addition, pairwise comparison also indicated an improvement in proactive stability from pre- to post-training only at *P*1 ($P1_{post}$_PD > $P1_{pre}$_PD, $p=0.028$). Further, there was no significant difference in reactive stability between $P1_{pre}$ and $P1_{mid}$ ($P1_{pre}$_RD = $P1_{mid}$ _RD, $p=0.245$); however, reactive stability did significantly improve from $P1_{mid}$ to $P1_{post}$ ($P1_{post}$_RD^{-} > $P1_{mid}$_RD, $p=0.017$). Moreover, contrasts were also performed to break down the significant interaction between intensity and timing [F (3, 60) = 5.281, $p=0.003$]. These contrasts also revealed a significant interaction when comparing all intensity levels (*P*1–*P*5) to slip timing [(F (1, 20) = 12.788, $p=0.002$)], specifically finding that the improvement in stability from PD to RD was more pronounced for *P*1.

Partial scaling effect in proactive stability

There were significant differences in proactive stability across *P*1–*P*5 ($P1_{pre}$_PD, $P3_{pre}$_PD, $P4_{pre}$_PD and $P5_{pre}$_PD) [F (3, 63) = 3.085, $p=0.034$] during the ascending session. Pairwise comparisons revealed that proactive stability improved significantly from $P1_{pre}$ to $P4_{pre}$ ($p=0.033$) and from $P1_{pre}$ to $P5_{pre}$ ($p=0.005$) (Fig. 3). However, reactive stability was not significantly different across any intensity level ($P1_{pre}$_RD, $P3_{pre}$_RD, $P4_{pre}$_RD and $P5_{pre}$_RD) during the ascending session [F (3, 63) = 0.626, $p=0.601$] (Fig. 3).

Mechanism of stability control

Linear mixed models indicated that overall $P_{COM/BOS}$ at PD was a significant predictor of stability ($p<0.001$) such that an increase in stability was associated with an anterior shift in $P_{COM/BOS}$ at PD (proactive stability = $0.14+0.39\times P_{COM/BOS}$), however, $V_{COM/BOS}$ at PD did not significantly predict the stability ($p>0.05$) (Fig. 4a). Further, linear mixed models revealed that the anterior shift of $P_{COM/BOS}$ at PD was correlated with a shorter step length before slip onset ($p<0.001$, $P_{COM/BOS}=0.54–3.2\times$ proactive step length); however, there was no correlation between $P_{COM/BOS}$ and trunk angle at PTD ($p>0.05$) (Fig. 4b). The improvement in stability at RD was associated with a corresponding anterior shift in $P_{COM/BOS}$ ($p<0.001$) and a faster $V_{COM/BOS}$ ($p<0.01$) (reactive stability = $0.02+0.46\times P_{COM/BOS}+0.89\times V_{COM/BOS}$) (Fig. 5a). The anterior shift in COM position relative to the BOS was associated with an increased compensatory recovery step length ($p<0.001$, $P_{COM/BOS}=0.44-1.44\times$ recovery step length) and a backward trunk extension ($p=0.002$, $P_{COM/BOS}=0.6+0.02\times$ trunk angle) (Fig. 5b).

Discussion

The current findings partially supported our first hypothesis that an "ascending-mixed-intensity" treadmill training paradigm could induce improved adaptive changes in proactive

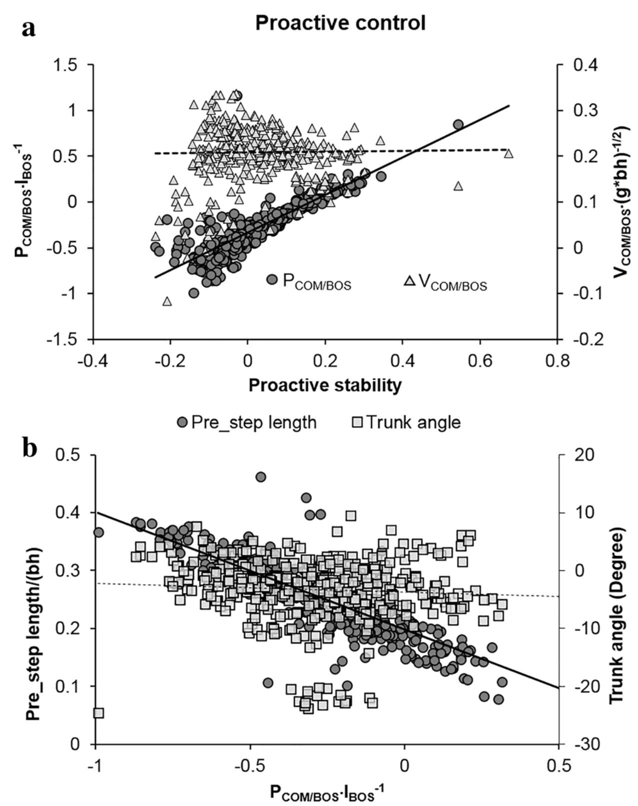

Fig. 4 Mechanism of proactive stability control. **a** The line of fit at total between proactive stability and COM position ($P_{COM/BOS}$) (solid line) and velocity ($V_{COM/BOS}$) (dashed line) relative to the BOS across all trials. **b** The line of fit at total between $P_{COM/BOS}$ and pre-step length normalized by individual's body height (bh) (solid line) and trunk angle (dashed line) across all trials. $P_{COM/BOS}$ was normalized to individual's foot length (l_{BOS}) and $V_{COM/BOS}$ was normalized to a dimensionless fraction of square root of gravity (g) and body height (bh). The significant predictors are indicated by $*p<0.05$

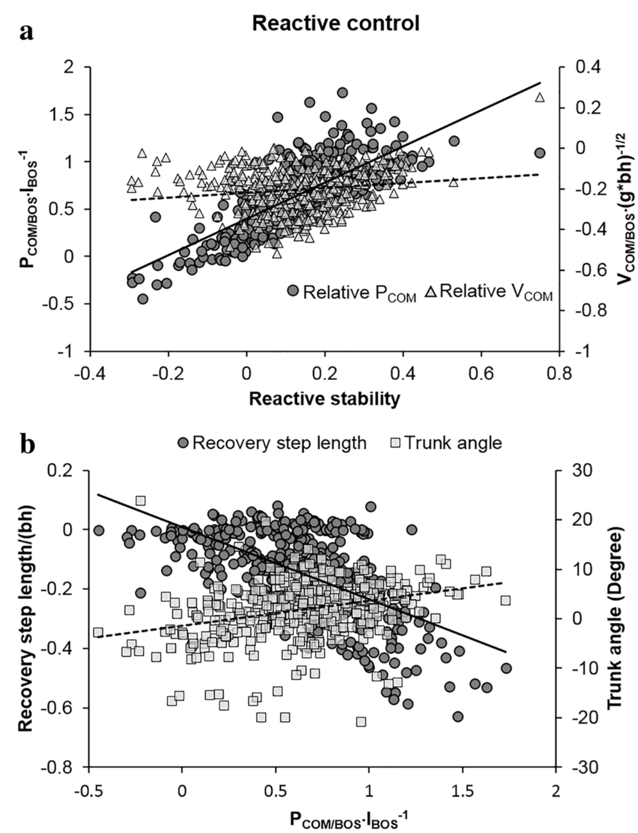

Fig. 5 Mechanism of reactive control. **a** The line of fit at total between reactive stability and COM position ($P_{COM/BOS}$) (solid line) and velocity ($V_{COM/BOS}$) (dashed line) relative to the BOS across all trials. **b** The line of fit at total between $P_{COM/BOS}$ and recovery step length normalized by individual's body height (bh) (solid line) and trunk angle (dashed line) across all trials. $P_{COM/BOS}$ was normalized to individual's foot length (l_{BOS}) and $V_{COM/BOS}$ was normalized to a dimensionless fraction of square root of gravity (g) and body height (bh). The significant predictors are indicated by $*p<0.05$

and reactive control; however, maximum improvement was seen at a lower intensity. In addition, our second hypothesis that participants would demonstrate a positive scaling effect in proactive and reactive stability was also only partially supported, as this positive scaling effect was only seen for proactive stability. Although participants did not improve reactive stability at higher intensities following exposure to lower intensities, subjects did maintain their reactive stability control when receiving increasingly challenging, higher-intensity disturbances.

Older adults demonstrated improvements in proactive stability from pre- to post-training at the lowest intensity level ($P1_{post} > P1_{pre}$) and between intensities from $P1$ to $P4$ and $P5$ in the ascending session. A trial-to-trial improvement in proactive stability has been similarly reported in young and older adults following exposure to repeated over-ground slips (Bhatt et al. 2006b; Pai et al. 2010). Similar to that demonstrated in these previous over-ground slip studies, proactive adjustments in stability during treadmill-induced slips were associated with an anterior shift of COM position (Fig. 4a) relative to the BOS, but not associated with COM velocity (Fig. 4a). Further, the anterior shift in relative COM position was associated with a decrease in pre-slip step length (Fig. 4b). The decreased pre-slip step length was also reported to be one of the feed-forward adjustments before slip onset in the over-ground slip studies in both young and older adults (Bhatt et al. 2006b; Pai et al. 2010). It could be possible that the proactive adjustment acquired from the current slip adaptation might pose a threat to other conditions such that a forward shifted center of mass position after repeated slips increases the risk of forward loss of balance after a trip. However, previous studies have reported that with receiving mixed slips and trips, participants could demonstrate more effective reactive responses and lower their risk of falls in comparison to their controls, despite limited early interference resulting from the different task types (Bhatt et al. 2013; Okubo et al. 2018). Therefore, the improvement in reactive stability could be an essential factor against perturbation-induced balance loss and, hence, is of great importance. Future studies should be designed to examine the effect of combined slip and trip training on trial-to-trial adaptive changes.

For reactive stability, participants also demonstrated post-training improvements at $P1$ ($P1_{post} > P1_{pre}$) and $P3$ ($P3_{post} > P3_{pre}$). A greater reactive stability was predominantly associated with an anterior $P_{COM/BOS}$ at recovery foot touch down, as opposed to being associated with a faster $V_{COM/BOS}$ (Fig. 5a). Further, the change in $P_{COM/BOS}$ was also predominately influenced by an increase in compensatory step length rather than an increase in trunk angle. The increase in compensatory step length enhances one's ability to protect against a backward loss of balance by establishing a new functional BOS (Pai et al. 2000). This relationship was consistent with findings for the treadmill-stance slip (Patel and Bhatt 2015, 2016).

The improved reactive stability at $P1_{post}$ compared with $P1_{pre}$ could have been influenced by the improvement in proactive stability; however, such improved feed-forward adjustment was not sufficient to prevent balance loss and eliminate the need to take a compensatory step to induce a "walk-over" strategy, as previously reported in the overground slip paradigm (Bhatt et al. 2006b; Pai et al. 2010). Additionally, the pre- to post-training changes in reactive stability (at compensatory step touchdown, TD) at $P1$ and $P3$ were significantly greater than the pre- to post-training changes in proactive stability at those levels (PD) (Fig. 3, Panels a, b). Further, because the treadmill perturbation was provided using a motorized belt which would have prevented participants from proactively altering the perturbation intensity, the improvements seen could reflect a pure training-induced improvement in reactive stability control.

Taken together, these findings suggest that the CNS predominantly relies on a feedback system, such as increasing compensatory step length, during experimenter-controlled perturbations (i.e., a treadmill-induced slip). Conversely, during subject-controlled perturbations (i.e., an over-ground slip perturbation which allows one to actively modulate control of the BOS and, hence, modulate slip intensity), the CNS relies on feed-forward control to proactively modulate protective recovery responses.

It should be noted that the proactive adjustments in stability control and pre-step length for treadmill-gait slips were not seen during adaptation to treadmill-stance slips (Patel and Bhatt 2015, 2016). This might due to differences in balance control between static and dynamic movements. In the upright standing position, an anterior shift of $P_{COM/BOS}$ would cause a risk of balance loss; however, during locomotion, a forward step can be used to maintain stability during such a change (Maki and McIlroy 1997; Pai and Patton 1997). Additionally, although participants in stance perturbation studies did develop a central set and had knowledge of the upcoming perturbation because the starting position was normalized (i.e., maintain an erect posture), they could only potentially make anticipatory postural adjustments and did not have a chance to make visible kinematic movements.

It is also important to recognize that even though there were proactive improvements pre- to post-training, these improvements were not seen at all levels. This lack of proactive improvement for other intensity levels could be due to the demonstrated and hypothesized positive scaling effect for proactive stability in the ascending session. First, there was a significant increase in proactive stability within each initial block at $P1$, $P2$, and $P3$ (Table 3). Second, due to such increase within each block, proactive stability was already increased and, therefore, remained at that higher value prior to experiencing the first exposure to $P4$ and $P5$. Given the limitation of the pre-set speed of the treadmill protocol, the ability to induce a proactive change would be limited to an anterior shift in $P_{COM/BOS}$ by modifying step length or altering trunk angle. Therefore, it is possible that the improved proactive stability reached after three intensity blocks of repeated slips ($P4_{pre} > P1_{pre}$) was already at its maximum steady state for improvement, and, hence, no further improvement was seen from pre- to post-training at the higher intensity levels.

With regards to reactive control, another important difference between studies which one should be aware of is that the lack of adaptation in control of trunk angle demonstrated by older adults in the current study varied from that of young adults in the previous treadmill-stance slip study. Patel and Bhatt (2016) reported a trend of decreased trunk extension with a forward shift of $P_{COM/BOS}$ in young adults at recovery touchdown which differed from our results. However, the

Table 3 Mean value of proactive stability in the ascending session for the 1st slip trial and the 4th slip trial within blocks at intensity levels of $P1$, $P2$, and $P3$

Proactive stability	$P1$	2nd $P1$	$P2$	$P3$
1st slip (SD)	−0.022 (0.096)	−0.021 (0.101)	−0.006 (0.093)	−0.010 (0.110)
4th slip (SD)	0.059 (0.089)	0.045 (0.172)	0.059 (0.110)	0.048 (0.118)
p value	<0.001	0.026	<0.001	0.005

$p < 0.05$ indicates a significant difference between the 1st slip and 4th slip at each intensity level slip intensity adopted in that study was much higher than in the current study (with the acceleration for the highest intensity being 16.75 m/s^2 instead of 6 m/s^2). This might suggest that aging could affect kinematic control of recovery strategies and/or that the extent of kinematic parameterization of recovery strategies could be intensity dependent.

Additionally, it is necessary to highlight that older adults in the current study did not demonstrate any improved reactive stability control from pre- to post-training at higher intensity levels ($P4_{post}$ and $P5_{post}$). Such results could be postulated to result from either a steady state or saturation reached within the reactive adaptation system for the given perturbation magnitude and/or from an insufficient practice dosage at the higher intensity levels. However, the results most likely suggest that the training dosage was critical for the extent of immediate adaptation demonstrated. The improvement in reactive stability control was most prominent at $P1_{post}$ and participants received the most intensive training dosage between $P1_{pre}$ and $P1_{post}$. When examining mid-adaptation at the lower level intensity ($P1_{mid}$), there was no improvement demonstrated compared to $P1_{pre}$; however stability for $P1_{post}$ was significantly greater than for both $P1_{pre}$ and $P1_{mid}$. Albeit, given that the results showed an improvement in reactive stability at lower intensities only after exposure to higher level intensities, it is possible that participants could have shown improvements in $P4$ and $P5$ levels if they were exposed to higher levels of intensities and subsequently re-exposed to levels $P4$ and $P5$.

With regards to the results for the second hypothesis, although scaling was seen for proactive stability, older adults did not demonstrate any between-intensity, successful scaling of reactive stability control, with exposure to slips at a lower intensity failing to improve reactive stability when exposed to slips at a higher intensity. Greater slip perturbation intensities (higher belt accelerations and increased slip distances) induce a greater balance loss, and recovery from such a balance loss is determined by the intensity-dependent modulation of the recovery response, mostly demonstrated in the form of magnitude scaling of the recovery response, such as in the form of increased recovery steps or a longer compensatory step length (Patel and Bhatt 2015; Sung and Danial 2018). Recent studies have reported that young adults could demonstrate improved reactive stability during higher-intensity treadmill-stance slips after receiving a single session of repeated treadmill-stance slip training at a lower intensity level (Patel and Bhatt 2015), and such scaling was even seen to occur after receiving a single slip exposure (Patel and Bhatt 2016). However, while young adults did demonstrate appropriate scaling to novel increasing intensity slips, older adults only demonstrated partial modulation. Recovering from an unexpected slip with increased severity induces a changed pattern of muscle activation in the trailing (i.e., peak magnitude of the vastus lateralis) (O'Connell et al. 2016) and/or the stance (i.e., onset of knee muscle latency) (Chambers and Cham 2007) limb, and, compared with older adults, young adults demonstrated longer and more powerful muscle activation with increased slip intensity (Chambers and Cham 2007). This age-induced difference might explain why older adults failed to improve reactive stability during slips at a higher intensity level even after receiving slips at a lower intensity level. However, although there was no improvement in reactive stability control between the ascending intensities (i.e., $P1$ vs $P3$, $P3$ vs $P5$), older adults did maintain their reactive stability, as opposed to having their stability deteriorate, as slip intensity increased (Fig. 3). Thus, the partial scaling observed is postulated to be because the initial block of training at a lower intensity level could have elicited a priming effect where the previous stimuli from the lower level prompted an optimal (if not better) recovery response to novel exposures to subsequent higher-intensity slips (Hauptmann and Karni 2002). This reflects the CNS's ability to select a proper motor response to an expected, related perturbation during the next movement in an incremental learning model (Wei et al. 2010) based on previous contextual information (Imamizu et al. 2007). Such a scaling phenomenon has been known to lead to generalization, and hence could possibly explain the overground generalization effects observed after exposure to an ascending-mixed-intensity protocol.

For this study, and others like it, dosage encompasses a variety of factors, including repetition of perturbations, intensity of perturbations, and number of training sessions, and it was important to evaluate the efficacy of the training dosages to make suggestions for future studies. In a previous recent study, Patel et al. (2018) reported a reduction in the number of compensatory steps taken at even the highest perturbation intensity level after a multi-session, ascending-intensity treadmill-gait slip training paradigm was applied to young adults. However, our training, which only involved a single training session, lower intensities, and fewer repetitions of perturbations than the previous study, demonstrated no significant training-induced reduction in the number of recovery steps, although there was a trend of decreasing mean value of steps (Table 2). It is, therefore, postulated that the current treadmill dosage (the number of trials within a session and the number of sessions) might not be sufficient to reduce recovery steps in older adults for the challenging levels of perturbation intensity provided, but the training dosage was designed this way to be tolerable for older adults, and any future changes to this dosage should be assessed for tolerability by these older adults.

Although our study did only partially show improved adaptive changes in proactive and reactive control, and participants only demonstrated a positive scaling effect for proactive stability, the results of the study are important and current findings shed light on the underlying mechanism of the previously shown positive generalization from treadmill-gait slips to over-ground slips in young and older adults (Lee et al. 2016, 2018; Liu et al. 2016; Wang et al. 2018; Yang et al. 2013). It has been reported that a single session of treadmill-gait slip training could improve stability control during a novel over-ground slip and, hence, reduce the rate of falls during over-ground locomotion in both young and older adults (Lee et al. 2016, 2018; Liu et al. 2016; Wang et al. 2018; Yang et al. 2013). Specifically, Lee et al. (2016) and Liu et al. (2016) reported that a higher intensity could yield better improvements in stability control upon encountering a slip during over-ground walking. Unfortunately, although generalization results were previously reported, none of these studies reported results from an acquisition session to demonstrate immediate training-induced adaptations in stability control during treadmill-gait slip training. In our study, we saw some similarity in adaptation mechanisms between over-ground gait slips and treadmill-gait slips (as previously discussed) which could better explain the findings of reduced over-ground falls seen in these previous studies. This finding is crucial, because it helps confirm that the acquired fall-resisting skills from the treadmill-slip training did actually result in improved stability during the over-ground slip. Thus, it could be postulated that the positive generalization from treadmill-gait slips to over-ground gait slips was due to the training-induced improved control of proactive and reactive COM state stability which resulted from parameterization of step length in anticipation of (pre-slip step length) and in response to (recovery step length) the gait slip perturbation.

The findings of this study must be interpreted in light of its limitations. First, treadmill slips in the study occurred during either the double-stance or single-stance phase of treadmill gait, whereas most over-ground slips in one's daily living occur during initiation of the double-stance phase (at heel strike when the utilized coefficient of friction for the slipping foot–floor interface exceeds the available coefficient of friction while the trailing foot is on the ground) (Cham and Redfern 2002; Hanson et al. 1999; McGorry et al. 2010; Redfern et al. 2001). For a double-stance slip, the execution of an efficient compensatory step for recovery follows an order of rapid unloading of the leg (lift-off the ground), a swing phase, an effective landing (touchdown), and a subsequent loading (Wang et al. 2017). However, treadmill slips induced in the single stance do not follow this order for compensatory stepping, and the swing phase usually demonstrates landing and subsequent loading with initiation of a second compensatory step. Nonetheless, all slips were limited to occur within one's early swing phase (first 30% of stance phase), and the first compensatory step represents participants' prompt reactive response to maintain their stability and prevent a backward balance loss (Yang et al. 2008) by bringing their COM closer to the BOS. Second, it remains unknown whether older adults could improve their reactive stability at higher levels (*P*4 and *P*5) after exposure to an even larger slip intensity (larger than *P*5), after additional dosage at higher levels within the same session (more slip repetition at *P*4 and *P*5), or after incorporating multi-session training. Finally, retention of the training effect from such a single session of treadmill-slip perturbations remains unknown. Protocol-wise, the current design only represents one of many practice dosages (combination of slip intensity and the number of slips at each intensity) which could yield training effects to successfully reduce fall-risks. Additionally, future studies are necessary to determine whether the current findings could be applied to older adults whose locomotor adaptability might be impaired by neurological diseases.

In summary, a single session of repeated treadmill-gait slips can elicit improved proactive and reactive stability control in older adults. This study sheds light on the application of such a convenient treadmill-slip device as an alternative intervention to improve reactive responses to postural disturbances and prevent balance loss by enabling individuals to practice taking a compensatory recovery step. Current findings also suggest that practice dosage with higher slip intensity and more slips might yield larger immediate adaptive improvements; however, further experimentation is needed to confirm this.

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Compliance with ethical standards

Conflict of interest The authors have no conflicts in the manuscript.

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