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Treadmill-based gait-slip training with reduced training volume could still prevent slip-related falls

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ABSTRACT

Background: Treadmill-based gait-slip training shows to be effective in reducing the risk of slip-related falls. In previous relevant studies, the number of repeated slip perturbations ranged from 12 to 30.

Research question: It is unclear if a reduced number of treadmill-slips can still yield adaptive strategies to lower the likelihood of falls after a slip over ground. This study examined if eight repeated slips on a treadmill reduced the risk of falls among young adults when they were exposed to a novel overground slip.

Methods: Forty-three healthy young adults were randomized into either training or control group. The training group underwent an 8-slip perturbation training procedure on a treadmill while the control group received the same number of normal walking trials on the same treadmill. Following the training, both groups were exposed to an unrehearsed slip during overground walking. Their body's reactions to the novel overground slip were collected by a motion capture system.

Results: The training group exhibited significantly better reactions to the slip than did the control group, evidenced by the lower fall proportion and improved dynamic stability at recovery foot touchdown during the overground slip. No improvement in dynamic stability was detected in the training group at the slipping foot touchdown and recovery foot liftoff.

Significance: The results suggested that the shortened perturbation training program may be efficacious in improving responses to a novel overground slip but may not be as effective as protocols using greater number of slips. This study could provide guidance for selecting the number of slips for future perturbation-based training protocols.

1. Introduction

Falls are a major cause of serious injury or worse in the elderly [1]. Backward falls resulting from slips account for up to 25% of hip fractures which constitute disastrous medical and socioeconomic consequences [2]. Considerable efforts have been dedicated to develop effective fall prevention interventions for older adults [3].

According to the task specificity principle of training [4], an environment exposing older adults to repeated perturbations (like a slip) could develop them the necessary neurophysiological and sensorimotor skills to avoid an actual fall should it occur outside the training environment. As an option to creating such an environment, perturbation training focuses on forcing individuals to adapt to a disturbed supporting surface [5]. Due to the plasticity of human spinal locomotor networks, which are likely involved in executing the recovery step following a disturbance to a regular gait, the repeated perturbation stimuli to the Central Nervous System (CNS) could induce stored motor programs that prepare the CNS for future postural threats [6]. It facilitates the effectiveness of recovery from an external perturbation and reduces the consequences of the disturbance [5]. Previous studies showed that perturbation training improves balance recovery among adults when they experience a future slip or trip perturbation [7,8].

Treadmill-based perturbation training has been increasingly used to reduce fall risk [9–12]. Some of previous studies that examined how treadmill-based perturbation training reduces falls collected fall incidences using the self-report approach [11,13]. Because this approach primarily relies on recounting incidence based on memory, it may introduce inaccuracy to the falls data. Some other studies used a treadmill as both the training tool and test platform [10,14]. Given the same condition between training and testing sessions, it could bring bias to

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the results and hardly assess directly whether the training indeed reduces the likelihood of falls when individuals walk on the ground.

A few studies have exposed trainees to an overground slip after the treadmill training and suggested that the training could lessen the risk of overground slip-related falls. Whereas, the number of slip perturbations was relatively large in those previous studies (12 [9] and up to 30 [12]). An unanswered question is whether a reduced number of slip trials can produce analogous training effect. This is a prominent issue. Firstly, examining the effect of a smaller number of slips could provide guidance for future studies trying different numbers of treadmill-slips. Additionally, if a smaller number of slips yield similar training effect, we can save and reallocate the limited fall-prevention resources to those with heightened fall risk. Finally, some individuals (like frail seniors or individuals with movement dysfunctions) may not be in the physical condition to undertake a training protocol consisting of a large number of trials. These populations will benefit from a shortened perturbation training procedure.

Dynamic gait stability has been identified as a key risk factor of slip-related falls [15]. Based on a theoretical framework (the feasible stability region theory, or FSR) [16,17], dynamic gait stability is characterized by the kinematic relationship between the body's center of mass (COM) and its base of support (BOS) (Fig. 1) [15]. The examination of how perturbation training alters dynamic stability control could elucidate the mechanisms through which the training modifies the risk of slip-related falls.

The purpose of this study was to investigate if a treadmill-based perturbation training paradigm consisting of eight slips can reduce the overground slip-related fall among young adults. We hypothesized that the abridged version of treadmill-based perturbation training decreases fall incidences and improves dynamic stability responding to an overground slip among young adults.

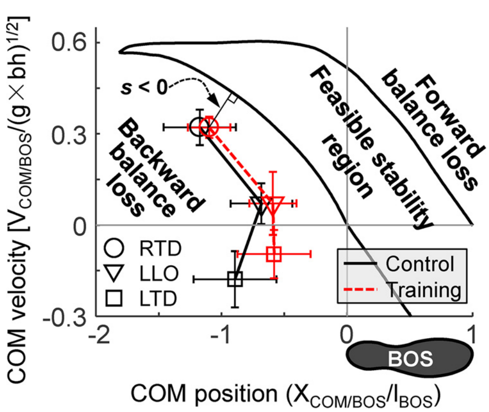

Fig. 1. Schematic illustration of the feasible stability region (FSR), which is enclosed by two boundaries: the threshold against backward balance loss (the lower boundary) and the one against forward balance loss (the upper boundary). The stability measurement (*s*, the length of the thin line) indicates the magnitude of the stability of the center of mass (COM) against backward balance loss, and is defined as the shortest distance from the COM motion state (i.e., the *x*-coordinate represents the COM anteroposterior position and the *y*-coordinate indicates its forward velocity relative to the base of support (BOS)) to the threshold against backward balance loss. When a COM motion state lies within the FSR, the stability consumes a positive value and this person is able to retain the body's balance without altering the present BOS. Nonetheless, a motion state falling below the threshold against backward balance loss (stability would be a negative measurement) brings instability that could result in a fall due to the inadequate forward momentum to carry the COM forward to the BOS. Also shown are the COM motion state at the instants of right (or slipping) foot touchdown (RTD, circle), left (or recovery) foot liftoff (LLO, triangle), and left foot touchdown (LTD, square) for both training and control groups during the overground slip trial. Position and velocity of the COM relative to the BOS are dimensionless as a fraction of l_{BOS} and $\sqrt{g \times bh}$, respectively, where l_{BOS} represents the foot length, g is gravitational acceleration, and bh is the body height.

2. Methods

2.1. Study design and participants

This study was a two-arm randomized controlled trial (Fig. 2a). Forty-three healthy young participants without known musculoskeletal/neurological disorders and orthopedic/cardiovascular conditions were enrolled (Table 1). After giving their written consent approved by the Institutional Review Board, they were randomly assigned into either the training or control group (Fig. 2a). The former underwent a perturbation training protocol while the latter received placebo training on the same treadmill. After the training, both groups were exposed to an identical overground slip.

2.2. Experimental protocol

After about 6 overground walking trials upon a 14-m walkway, all participants stepped onto a regular treadmill over which their comfortable treadmill walking speed was determined [18]. They were then directed to an ActiveStep treadmill (Fig. 2b, Simbex, NH) and donned a full-body harness tethered to an overhead arch. After three 30-sec walking trials at his/her pre-determined walking speed, each participant underwent three 30-sec trials with the belt speed of 1.2 m/s. The speed of 1.2 m/s was chosen based on the average comfortable treadmill walking speed across all participants (1.16 ± 0.14 m/s). This speed was also used to create the treadmill-slip profile (Fig. 2c). Such a standardized slip profile would eliminate the confounding effect from the uncontrolled gait speed between groups. Then, each group underwent their respective training protocol (either perturbation or placebo), followed by the overground slip test.

2.2.1. Training

The training group undertook 5 slips followed by 3 normal walking trials (at 1.2 m/s) and then 3 slips. The slip perturbation level was 12 m/s^2 of acceleration and 0.24 m of slip displacement [12]. For each slip, the belt began at a backward 1.2-m/s speed. After 10–12 regular steps, the belt suddenly accelerated forward to 1.2 m/s within 0.2 s following the touchdown of the front foot (Fig. 2c). After the first slip, participants were instructed that "What you just experienced was a slip. From now on, you may or may not be slipped on every trial. If a slip occurs, try your best to recover your balance and to continue walking forward." The control group underwent 11 normal walking trials on the treadmill at 1.2 m/s, which formed the placebo training protocol.

2.2.2. Overground slip

Following the training, all participants went back to the walkway and put on the harness which was connected to a loadcell and then a ceiling-mounted weight suspension system by ropes. Participants were instructed to face away from the walkway before each trial until they were told to turn around. When participants faced away from the walkway, the room lights were adjusted to their maximum level and the experimenter made noise in the middle of the walkway where the sliding device resides. Then, the lights were dimmed, and participants were asked to turn around and face the walkway. They were instructed to look straight forward and walk at their comfortable speed during all trials. They were also clearly told that no slip perturbation would happen during the first three trials. After completing these three trials, they were informed of the possibility of slipping on the subsequent trials. It was repeated that they should "try not to fall" after a slip occurred. During the next about six walking trials, each participant's starting position was adjusted to ensure their right foot to land in the middle section of a movable platform. The participant was then exposed to the novel overground slip during the next trial.

The overground slip was induced by a customized sliding device

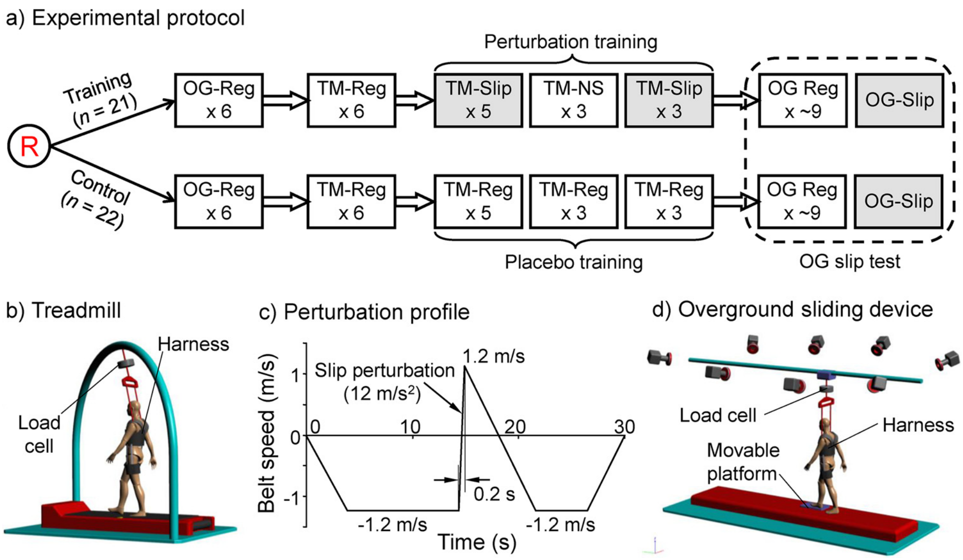

Fig. 2. Schematics of a) the experimental protocol, b) the ActiveStep treadmill used to produce slip perturbation during gait, c) the profile of the treadmill (TM) slip perturbation, and d) the sliding device for the overground (OG) slip test. After randomization, both training and control groups were given 6 overground regular (Reg) walking trials over a 14-m walkway followed by 6 TM regular walking trials. Then each group underwent their designated training protocol: perturbation training for training group and placebo training for control group. The perturbation training protocol consists of 8 treadmill-slip trials mixed with 3 non-slip (NS) treadmill walking trials. Each TM slip trial began with a 2-s ramp up, followed by a steady state with a backward-moving belt speed of 1.2 m/s. After 10–12 regular steps, approximately 80–120 ms later than the next touchdown, the belt was suddenly accelerated to 1.2 m/s forward within 0.2 s. On the other hand, the placebo training includes 11 regular treadmill walking trials. Next, both groups were brought back to the overground walkway. After about 9 times regular walking, the overground slip was induced by the sliding device embedded in the middle of the walkway. The sliding device consists of a movable platform which can travel smoothly forward up to 1.0 m. Participants were protected by a full-body safety harness on all the slip trials.

Table 1
Comparisons of the demographic and anthropometric information (in mean ± standard deviation) between the training and control groups. The knee strength capacity (both the extensors and flexors) was measured under the isometric condition at the right side on the Biodex System 3 (Shirley, NY).

Parameter	Control (n = 22)	Training (n = 21)	p-value
Age (years)	23.0 ± 3.87	22.6 ± 3.22	0.727
Gender (female)	9	14	0.091*
Height (m)	1.67 ± 0.09	1.70 ± 0.08	0.257
Mass (kg)	72.9 ± 18.0	74.9 ± 17.9	0.715
Knee extensor (Nm)	146.3 ± 48.2	154.4 ± 47.1	0.583
Knee flexor (Nm)	120.0 ± 37.5	119.9 ± 39.9	0.992

* Fisher's exact test was used.

which resided on the right side of the mid-section of the walkway (Fig. 2d). This device consisted of a linear railway upon which two bearings can smoothly travel. The bearings were attached to a movable platform. During normal walking trials, the railway was covered by a wooden plate of the same color as the walkway. The platform and the wooden plate were flush with the ground surface to reduce their visibility to the participants. The platform was firmly locked by two pins during normal trials. Participants could not feel any movement of the platform, reducing their prior knowledge about the impending slip. During all trials, the lights were dimmed to further lower the visibility of the movable platform. Immediately before the slip trial, the pins and the wooden plate were removed while the participants were facing away from the walkway. Due to the noise made by the experimenter between trials, it was impossible for participants to guess the location, timing, or mechanism of the slip perturbation. Upon the slip trial, when the participant stepped on the platform, his/her right foot would travel forward with the platform up to 1.0 m, creating a novel, large-scale slip perturbation.

The full-body kinematics of the overground trials were recorded using an 8-camera motion capture system (Vicon, UK) at 120 Hz from 27 reflective markers (26 on participants' body and one on the movable platform). The force exerted on the rope during the post-training overground trials was recorded by the loadcell at 600 Hz, synchronized with the motion capture system.

2.3. Data reduction

The overground slip trial was of our interest. 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 [19]. Locations of joint centers, heels, toes, and the platform were computed from the filtered marker positions. Three events: the touchdown of the right (or slipping) foot on the platform (RTD), the liftoff of the left (recovery) foot (LLO) and its touchdown (LTD) were decided based on the foot kinematics.

The loadcell force was used to determine the outcome (fall or recovery) of the overground slip trial. The slip outcome was classified as a fall if the peak loadcell force exceeded 30% body weight (bw) [20]. A recovery occurred when the moving average of the loadcell force over any one-second period did not exceed 4.5%bw [20].

The body COM kinematics were computed using gender-dependent segmental inertial parameters [21]. The two components of the COM motion state, i.e. its position and velocity, were calculated relative to the rear of BOS (i.e., the right heel) and normalized by foot length (l_{BOS}) and $\sqrt{g \times bh}$, respectively, where g is the gravitational acceleration and bh the body height. Dynamic stability was calculated as the shortest distance from COM motion state to the lower boundary of the FSR (Fig. 1) [16]. The COM position, velocity, and dynamic stability were calculated at the three events.

The duration of the double (from RTD to LLO) and single (from LLO to LTD) stance phases were also calculated. The displacement and velocity of the BOS in the anteroposterior direction were determined from the platform marker. The BOS displacement was converted by using its value at RTD as the reference. The platform velocity was calculated as the first order derivative of its displacement with respect to time. Both the BOS displacement and velocity were determined at LLO and LTD.

2.4. Statistical analysis

A χ^2 test was used to compare the fall proportion in response to the overground slip between groups. Independent t-tests were applied to compare the spatiotemporal measurements between groups. These measurements included the duration of single and double stance phases, COM position, velocity, and dynamic stability at all events, and the BOS kinematics at LLO and LTD. SPSS 24.0 (IBM, NY) was used for statistical analysis and a p value < 0.05 was considered significant.

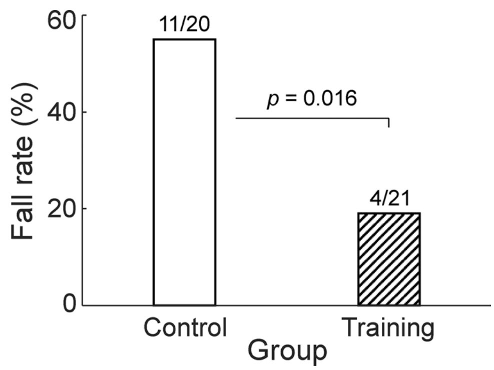

Fig. 3. Comparisons of the fall proportion between the training and control groups in response to the unexpected overground slip perturbation when participants walked over a sliding device in the middle of the walkway.

3. Results

The overground slip was invalid for two participants in the control group due to technical errors. Therefore, 20 and 21 participants respectively from the control and training group were included in the final analysis.

Upon the novel overground slip, 11 out of 20 (55.0%) and 4 out of 21 (19.1%) participants respectively in the control and training group fell ($\chi^2 = 5.707$, $p = 0.016$) (Fig. 3). Although both groups spent comparable time during the double stance phase after slip onset (0.148 ± 0.034 s for control vs. 0.155 ± 0.046 s for training, $p = 0.622$), the training group exhibited a statistically shorter single stance phase than the control (0.144 ± 0.069 vs. 0.185 ± 0.049 s, $p = 0.035$, Fig. 4a).

At both RTD and LLO, the training group showed similar COM position to the control group (RTD: −1.099 ± 0.169 vs. −1.174 ± 0.287, $p = 0.307$; LLO: −0.593 ± 0.188 vs. -0.683 ± 0.245, $p = 0.192$, Fig. 5a). Similarly, both groups exhibited alike COM velocity at RTD (0.321 ± 0.035 vs. 0.322 ± 0.058, $p = 0.973$) and LLO (0.071 ± 0.103 vs. 0.071 ± 0.067, $p = 0.991$, Fig. 5b). No significant difference was observed between groups regarding dynamic stability at RTD (-0.157 ± 0.044 vs. -0.165 ± 0.057, $p = 0.589$) and LLO (-0.236 ± 0.128 vs. -0.267 ± 0.114, $p = 0.420$) (Figs. 1 and 5c).

At LTD, individuals in the training group moved their COM more anteriorly (or closer) to the BOS compared to those in the control group (-0.582 ± 0.292 vs. −0.893 ± 0.330, $p = 0.003$, Figs. 1 and 5a). The training group demonstrated significantly less backward COM velocity relative to the BOS than the control group (-0.096 ± 0.080 vs. −0.178 ± 0.092, $p = 0.004$, Fig. 5b). The training group was significantly less unstable than the control group at LTD (-0.375 ± 0.162 vs. -0.566 ± 0.160, $p < 0.001$, Fig. 5c).

At LLO, the BOS slip kinematics did not display group-related difference (velocity: 1.138 ± 0.479 vs. 1.164 ± 0.308 m/s, $p = 0.840$, Fig. 4b; displacement: 0.063 ± 0.030 vs. 0.063 ± 0.028 m, $p = 0.969$, Fig. 4c). The BOS travelled more slowly (1.687 ± 0.343 vs. 1.919 ± 0.388 m/s, $p = 0.048$, Fig. 4b) with shorter displacement (0.259 ± 0.049 vs. 0.369 ± 0.077 m, $p < 0.001$ Fig. 4c) at LTD in the training group than in the control.

4. Discussion

The study examined the effect of a shortened treadmill-based perturbation training paradigm on reducing slip-related falls among young adults. Our results supported the hypothesis that shortened, single-session treadmill-based perturbation training could lessen the fall incidence and improve dynamic stability responding to a novel overground slip. The training group experienced a lower fall rate than the control group (19.1% vs. 55.0%).

The lower fall incidence in the training group than in the control implies that the fall resistance skills obtained from the treadmill training could be transferred to the overground slip. Previous studies suggested that humans can quickly adapt their gait pattern to potential slip surfaces when they are aware of the possibility of slips during both overground [22] and treadmill [23] walking. Therefore, a factor leading to the reduced fall proportion in the training group is the prior experience of slip disturbance during the training. Owing to the pre-existing experience, participants in the training group demonstrated a better and quicker reaction to the slip than their control counterparts, as evidenced by the shorter single-stance phase (Fig. 3a), the better control of BOS movements (Fig. 4b and c) and dynamic stability (Figs. 1 and 5) at LTD.

At LTD during the overground slip, participants in the training group demonstrated significantly less instability than the control group although the stability values were negative. Based on the FSR framework, a negative dynamic stability value means an unstable state

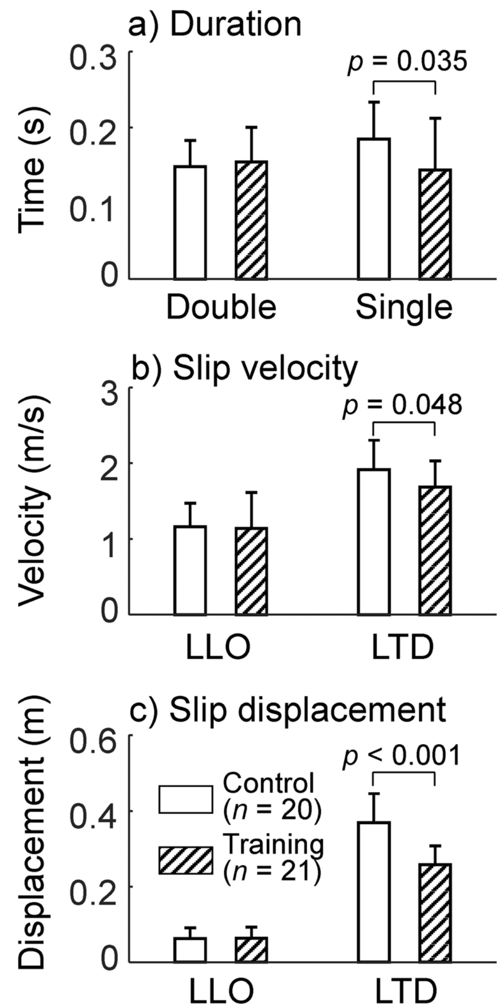

Fig. 4. a) Group mean (column height) and standard deviation (bar) of the elapsed time in seconds for both groups of their double and single stance phases during the overground slip. The double stance phase is the one from right foot touchdown (RTD) to the left foot liftoff (LLO) while the single stance phase is defined as the duration between LLO to left foot touchdown (LTD). Also shown are the comparisons of (b) the slip velocity and (c) slip displacement of the base of support (BOS) at LLO and LTD between the control and training groups during the novel overground slip. For the slip displacement, it is calculated from the position of the movable platform marker and referenced to the BOS's position at RTD. The BOS velocity is computed as the first-order derivative of the BOS displacement with respect to time.

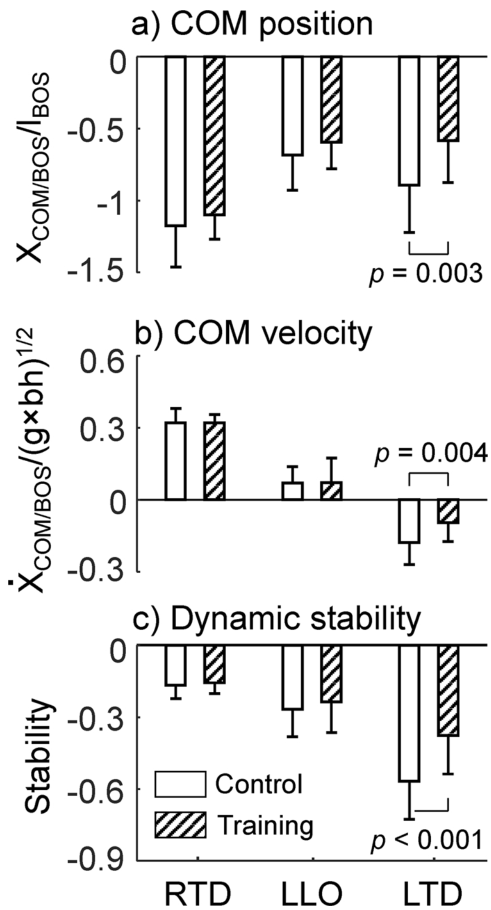

Fig. 5. Comparisons of (a) the center of mass (COM) position, (b) COM velocity, and (c) dynamic stability at the right foot touchdown (RTD), the left foot liftoff (LLO) and its touchdown (LTD) between the control and training groups. Both the COM position and velocity were relative to the rear edge of the base of support (BOS) and respectively normalized by foot length (l_{BOS}) and $\sqrt{g \times bh}$, where g represents the gravitational acceleration and bh the body height. Stability is calculated as the shortest distance from the given COM motion state (i.e. its position and velocity) and the computer-predicted threshold against backward balance loss (Fig. 1).

against backward balance loss because one's COM has insufficient forward momentum to catch the BOS [24]. Thus, both groups experienced a backward balance loss. Nevertheless, due to the smaller instability, individuals in the training group fell less than the control group (Fig. 5c). According to the FSR theory, the low instability among the training group were achieved by shifting the COM closer to the BOS and moving the COM backward more slowly compared to the control group (Figs. 1 and 5).

The better control of the COM stability in the training group could be mainly contributed to the enhanced control of the BOS movement compared to the control group. At LTD, the BOS travelled a shorter distance at a slower speed among the training group than the control (Fig. 4b and c). A shortened single stance phase also contributes to the reduced slip displacement in the training group. As dynamic stability is determined by the relative movement between COM and BOS, the control of BOS movement during a slip is essential to prevent balance losses or falls [25]. The improved BOS movement brought the COM motion state closer to the threshold against backward balance loss, thus enhancing dynamic stability in the training group (Fig. 5c). The improved stability in turn reduced the likelihood of falls in this group. Such a better control could be attributable to the prior treadmill-slip experience in the training group, but not the control group. Our observations regarding the improved BOS kinematics control concur with the previous study [12].

After a slip, to regain body balance and prevent an actual fall, one must generate quick and appropriate corrective reactions [15,26]. Most notable is the recovery stepping during which the recovery leg must provide sufficient anti-gravity support to prevent limb collapse [26,27]. Adequate lower extremity strength is demanded to execute this strategy. In this study, participants did not show group-related difference in the knee joint strength capacity (Table 1). Given that the knee muscle strength could be used to reflect the overall limb muscle strength among healthy adults, it is reasonable to spectulate that the lower limb muscle strenght is comparable between groups in the present study. Therefore, the speed at which one executes the recovery step becomes a critical factor leading to falls after a slip. Participants in the training group completed the recovery step faster than the control group as indicated by the shorter single-stance phase (Fig. 3a, $p = 0.035$). This would have played a vital role to reduce fall incidents in this group since a quickly-deployed compensatory step reestablishes the BOS and provides limb support to stop or reverse the falling.

Dynamic stability did not exhibit significant group-related difference at RTD and LLO while previous studies have observed that young adults appeared to improve dynamic stability at RTD and LLO after treadmill training [12]. This difference could be related to the training dosage. The number of treadmill slips was eight in this study while participants in previous studies experienced up to 30 slips. Our shortened version of perturbation training may not be adequate to induce the adaptive changes at RTD and LLO. Despite the less-intensive training in the present study, it was still able to improve dynamic stability at LTD to an extent which reduced the fall incidences in the training group, confirming previous findings [12].

Our study has limitations. First, the retention of the effect from this shortened training protocol was not examined. It remains unknown how long its training effect could persist. Second, the slip in this study could be deemed as an anticipatory slip, which differs from an unexpected slip in the real life. It is unclear to what extent the findings from this study can be transferred to a real-life situation. Third, the training was based on a blocked design without involving randomized training. Such a training protocol may not achieve a training outcome as effective as a combined design including both blocked and randomized practice. All issues need further investigations.

In conclusion, our results indicated that a limited version of treadmill-based slip perturbation training protocol can still improve dynamic stability control and reduce falls after a novel overground slip. The finding could provide guidance for the design of treadmill-based perturbation training for reducing falls.

Conflict of interest

The authors declare no conflict of interest.

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