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GENERALIZATION OF TREADMILL-SLIP TRAINING TO PREVENT A FALL FOLLLOWING A SUDDEN (NOVEL) SLIP IN OVER-GROUND WALKING

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Abstract

The purposes of the study were to determine 1) whether treadmill-slip training could reduce the likelihood of falls during a novel slip in over-ground walking, and 2) to what extent such (indirect) training would be comparable to (direct) over-ground-slip training. A treadmill-slip training group (Group A, n=17) initially experienced repeated perturbations on treadmill intended to simulate forward-slip in over-ground walking. Perturbation continued and its intensity reduced when necessary to ensure subjects' successful adaptation (*i.e.*, when they could land their trailing foot *ahead* of the slipping foot in at least 3 of 5 consecutive trials). They then experienced a novel slip during over-ground walking. Another 17 young adults in Group B experienced an identical novel slip that served as the controls. They then underwent more slip trials during over-ground walking. Their 16th slip trial was analyzed to represent the over-ground-slip training effect. Eight subjects (47%) in Group A fell upon their first treadmill slip, while all adapted successfully after a minimum of 15 slip trials. Upon the novel slip during over-ground walking, none of them fell in comparison to four subjects (23.5%) fell in Group B upon the same trial (p<0.05). Group A's control of stability, both proactive and reactive, was significantly better than that of Group B's on their first over-ground slip, while the level of improvement derived from indirect treadmill training was not as strong as that from direct over-ground-slip training, as demonstrated in Group B's 16th slip trial (p<0.001). These results clearly demonstrated the feasibility of fall reduction through treadmill-slip training.

Keywords

perturbation; motor program; spatial transfer; stability control

Introduction

Falls pose a significant health threat to elderly (Baker and Harvey, 1985; Tinetti, 2003). Slips comprise 40% of outdoor falls among older adults (Luukinen et al., 2000). Growing efforts have been directed towards designing and implementing fall prevention programs

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Conflict of Interest Statement

None declared.

ranging from education only (Boardman et al., 2010; Hakim et al., 2007; York et al., 2011) to multi-factorial balance training (e.g. combined strengthening and balance exercises) (Carter et al., 2001; Rubenstein and Josephson, 2006; Tideiksaar, 1987; Tinetti et al., 1994) to alternative therapeutic approaches (e.g. Tai-Chi) (Kessenich, 1998; Wolf et al., 2003) and to balance training under various sensory conditions (Hu and Woollacott, 1994).

An emerging paradigm relies on perturbation training to reduce fall-risk (Bhatt et al., 2006; Mansfield et al., 2010; Prakriti and Lockhart, 2012; Shimada et al., 2004; Yungher et al., 2012). This approach focuses on adaptation to perturbation rather than on self-motivated improvements of one's volitional performance, because perturbation-induced errors that a subject may not consciously notice can still modify future motor plans for task-related improvements. With repeated-slip exposure, for instance, the central nervous system (CNS) adopts proactive (feed-forward) and reactive control strategies that, even if unconscious, can improve the center of mass (COM) stability relative to the slipping base of support (BOS) and improve limb support against gravity, both of which can lead to the reduction of the likelihood of falls.

Such training-induced adaptive changes have been observed in a laboratory environment, equipped with low-friction moveable platforms to produce unannounced, repeatable slips during daily activities of living, such as sit-to-stand and walking (Pai and Bhatt, 2007). Such perturbation training can reduce fall incidence among older adults from 50% upon the first encounter of a novel slip to 0% upon the final (24^{th}) slip during walking (Pai et al., 2010). These training effects can be retained for at least 6 months (Bhatt et al., 2012). While these results are very promising, the current method for inducing slips - using a long instrumented walkway with moveable platforms and overhead protective railing system - is often infeasible in the clinical and community settings, where most fall prevention training is performed. Consequently, t his could limit its clinic applicability and therefore its general appeal.

In contrast to the long walkway used to induce over-ground slip, treadmills are portable, and they can be used to deliver precisely controlled and highly reproducible perturbation (Cakit et al., 2007; Shimada et al., 2004). Further, it is also relatively easy and convenient to provide the requisite harness protection in a small and confined activity space during treadmill training. For these reasons, treadmills would be advantageous to use in clinical or community fall-prevention training. Despite these attractions, however, a central question remains: can treadmill-slip training transfer to fall-reduction during a novel slip recovery in over-ground walking? Can they also generalize from (indirect) repeated-slip training on treadmill to (directly) reduce falls during over-ground walking as occurring in everyday living?

The purposes of the study were to determine 1) whether treadmill-slip training could reduce the likelihood of falls during a novel slip in over-ground walking, and 2) to what extent such (indirect) training would be comparable to (direct) over-ground-slip training. We hypothesized that young adults' fall-resisting skills acquired from treadmill-slip training could help them to reduce the likelihood of falls from a novel slip during over-ground walking, resulting from the improvement in the control of stability and limb support (Hypothesis One). We also recognized that such indirect-training method might not be as effective as the (direct) repeated-slip training conducted during the over-ground walking. We therefore hypothesized that the direct training could be more effective than the indirect training in reducing falls and in improving the control of stability for slip recovery in over-ground walking (Hypothesis Two).

Methods

2.1 Subjects

Seventeen young adults (Group A, Table 1) were recruited to receive the treadmill-slip training (Figs. 1 and 2a). Another 17 young adults (Group B) received over-ground-slip training (Figs. 1 and 2b). This latter group wa s randomly selected from a sample of 39 subjects who experienced a total of 24 slips during their over-ground walking in previous studies (Bhatt and Pai, 2008; Bhatt et al., 2006). All subjects gave informed consent for participation in the experiments, approved by Institutional Review Board.

2.2 Study design

Baseline (*unperturbed walking*) *trials* were recorded to detect any between-group difference or any treadmill-training effect on a person's spontaneous gait pattern. Subjects in both groups first walked repeatedly (five times for Group A and ten for Group B) on an instrumented pathway (7m × 1.5m, Fig. 2b) as their *baseline trials (pre-training)*. They were told to walk in any manner and at any speed they preferred, and that a slip "may or may not" occur. Thus the slip, when it occurred later for the first time, would be unannounced and difficult to predict. After their baseline trials, subjects in Group A received treadmill training before returning to the same walkway for another five baseline trials *(post-training)*.

Both groups A (in the present study) and B (from precious studies) had approximately the same amount of over-ground walking experience (a total of ten baseline trials) before they encountered their first, novel slip (A_S1 or B_S1). Group A would have already received treadmill training before encountering this slip, whereas Group B had not received any training prior to the same slip. Therefore, Group B's first slip became the control for Group A's treadmill training in order to test Hypothesis One (Fig. 1). In previous experiments, subjects in Group B had experienced a total of 24 slips during over-ground walking (Bhatt et al., 2006). Because Group B's 16^{th} slip trial (B_S16) could demonstrate the comparable post-training effect that would be shown in Group A's post-training trial A_S1 after its minimum number of 15 repeated slips during treadmill training (Fig. 3), this trial was analyzed in order to examine Hypothesis Two (Fig. 1).

2.3 Experimental setup

The ActiveStep treadmill (Simbex, Lebanon, NH) was used to induce slip-like perturbation (Fig. 2a). Each slip trial began with 1.5-second ramp up, followed by a 4-second steady state with a *backward-moving* belt speed of 1.2m/s (Fig. 2c). After four to ten regular steps in each slip trial, at the beginning of the next single stance phase, without the subjects' knowledge, the top belt suddenly accelerated in the forward direction, which abruptly reduced its backward speed and thereby inducing a forward displacement of the subjects' BOS relative to their COM. The treadmill kinematics of each trial was fixed, as defined by a pre-programmed profile (Fig. 2c–d). Details about inducing slip-like perturbation on treadmill were provided in online supplement A.

Over-ground slips were induced on a pair of moveable platforms, each custom made and mounted on low-friction metal tracks supported by two individual force plates beneath the floor (AMTI, Newton, MA) (Yang and Pai, 2007). The two platforms were firmly locked in place when subjects walked along a 7-m over-ground walkway (Fig. 2b). An unannounced slip was induced upon a computer-controlled release of the locking mechanisms, which allowed the platforms to slide forward for 0.9m or more. All subjects wore a full-body safety harness, which was linked through a load cell (Transcell Technology Inc., Buffalo Grove, IL) to an overhead arch during treadmill walk (Fig. 2a) or to a ceiling-mounted trolley-and-beam system during over-ground walk (Fig. 2b).

2.4 Training and slip-test protocol

After their pre-training baseline walking trials and a 5-minute rest break, subjects in Group A stood on the treadmill and start to walk. They were told that they might experience “slip-like” movements on the treadmill “later”, but they should just “try to keep walking”. The training protocol was designed to augment movement error, followed by a progressive error-reduction scheme to mimic the spontaneous adaptive process observed during over-ground-slip training (Pai et al., 2010). Perturbation training began at a constant belt acceleration of $12 m/s^2$ for 0.2s, which resulted in a displacement of 0.24m (Fig. 3). This level of acceleration was comparable to that exhibited in the first, novel slip induced during over-ground walking (Table 2). Each subject experienced five consecutive slips at this perturbation level.

A subject’s successful response to any given perturbation level occurred when that subject did not fall nor take a recovery step that landed posterior to the stance foot in at least three of these five trials at that perturbation level. When his/her response was successful at that level (“Yes” in Fig. 3), the intensity of the next perturbation level would increase by $2 m/s^2$ in order to augment movement error. If the response was unsuccessful (“No”), the next intensity would reduce by $4 m/s^2$. Five consecutive slip trials were given at each perturbation level before the next profile was applied. Each subject completed training at his/her highest successful level (Fig. 3).

After the training, these subjects returned to the walkway where they underwent post-training baseline trials, before encountering their first, novel over-ground slip (A_S1). They had no knowledge about where, when and how that slip would occur. This novel slip concluded their test session. Subjects in Group B encountered an identical novel slip after their baseline walking trials without knowing how, when or where it would occur (B_S1). Without the knowledge of any upcoming trial conditions, subjects in Group B experienced eight repeated slips in the first slip block before a block of three nonslip trials, another eight slips, three more nonslip trials, and a final block of mixed slip-and-nonslip trials for a total of 24 slips (Bhatt et al., 2006).

2.5 Trial events, outcome variables and data reduction

Three baseline trials, A_5, A_10 and B_10, were analyzed (Fig. 1). Six outcome variables for baseline measurement [step length, foot angle, the COM motion state (i.e., its position and velocity), stability, and hip height] were calculated at right foot touchdown (RTD). Because this moment immediately preceded slip onset in slip trials, these variables can reveal training-induced alterations in proactive (feed-forward) control, which was characterized by changes in motor response performed prior to or in anticipation of a potential perturbation (Woollacott and Tang, 1997). Three slip trials, A_S1, B_S1 and B_S16, were also analyzed (Fig. 1). Six recovery outcome variables for slip trials (slip velocity, absolute COM velocity, its relative motion state, stability, and hip height) were calculated at recovery (left) foot liftoff (LLO) to detect any perturbation training effect on the reactive control. Reactive control was characterized by motor actions took place after the perturbation onset (Diener et al., 1988).

In all over-ground trials (slip and nonslip), every subject’s (both groups) full body kinematics, the ground reaction force (GRF) and the load cell force were recorded and synchronized with video recording. According to the study design, only these data were analyzed to make between- and within-group comparisons. During treadmill training, subjects’ motion on the treadmill was captured on video recorder, while load cell force and treadmill belt-pressure-sensor information was recorded. These data were only applied to determine the recovery outcome of each slip trial during treadmill training.

Kinematics of over-ground trials was recorded by an eight-camera motion capture system (MAC, Santa Rosa, CA). The step length during the baseline trials was calculated from the farthest distance of the left-to-right heel (*i.e.*, between their most posterior positions) during stance phase and normalized to the body height (*bh*). Foot angle was the angle between the sole and ground where a flat foot corresponded to zero degrees. The body COM kinematics was computed using gender-dependent segmental inertial parameters (de Leva, 1996) based on the filtered marker positions. Its relative position and velocity were referenced to the rear edge of BOS, and they were respectively normalized by foot length (l_{BOS}) and $\sqrt{g \times bh}$, where g represents the gravitational acceleration. The COM stability was evaluated as the shortest distance from the COM motion state to the stability limits in the state space (Yang et al., 2008a; Yang et al., 2008b). Hip height (quantifying limb support) was the vertical distance of the bilateral hip midpoint to the ground and normalized to *bh* (Yang et al., 2009). Timing of foot touchdown and liftoff was identified from the vertical GRF. Slip velocity was calculated as the velocity of the moveable platform. A fall was defined as if the peak force recorded by the load cell in the harness system exceeded 30% of body weight (Yang and Pai, 2011).

2.6 Statistical analysis

Independent *t*-tests were applied to determine any between-group difference existed in the six variables at RTD for baseline trials A_5 and B_10, and paired *t*-test examined any treadmill training effect on baseline trials A_5 and A_10 (Fig. 1). The training effect on fall reduction and the six recovery outcome variables was examined by applying χ^2 tests and independent *t*-tests, respectively. To reduce Type 1 error due to the multiple *t*-test comparisons, the Bonferroni step-down (Holm) correction was made. All statistics were performed using SPSS 17.0, and a significance level of 0.05 was used.

Results

Eight subjects in Group A (47.1%) fell in their first slip (distance: 0.24m; acceleration: 12m/s^2) on the treadmill and the remaining nine never fell. After 15 slips, seven subjects successfully reached their highest perturbation level at 8m/s^2; while other ten subjects reached their highest successful level at 6m/s^2 in 20 slips (Fig. 3). Treadmill training brought significant improvements in proactive control of stability against any potential risk of slip-related falls, characterized by more forwardly positioned COM (p<0.05 for A_5 vs. A_10) that led to greater COM stability in the post-training baseline trials (p<0.05 for A_5 vs. A_10). These subjects also adopted a flatfooted landing pattern (p<0.05 for both A_5 vs. A_10) at RTD, while they made little change in their step length, gait speed, and hip height (p>0.05, Fig. 4a, d, & e).

No between-group differences were observed in the baseline trials (p>0.05 between A_5 and B_10 for all variables, Fig. 4). Upon the novel slip, treadmill training significantly improved subjects' reactive control of stability (A_S1 vs. B_S1, p<0.001, Fig. 5e). In comparison to the controls, they displayed more forwardly-shifted COM position (A_S1 vs. B_S1, p<0.05, Fig. 5c) and faster relative COM velocity upon their LLO (A_S1 vs. B_S1, p<0.001, Fig. 5d). The latter resulted primarily from a significant reduction in forward slip velocity (A_S1 vs. B_S1, p<0.001, Fig. 5a), while the absolute COM velocity changed little (A_S1 vs. B_S1, p>0.05, Fig. 5b). Because of such improvements in the control of COM stability, no subjects from Group A fell during A_S1; while 23.5% (4/17) in Group B fell on B_S1 (χ^2 =4.53, p<0.05, Fig. 6).

No one in Group B fell upon B_S16 (Fig. 6). The direct training did lead to a further forward shift of the COM (A_S1 vs. B_S16, p<0.001, Fig. 5c), and even better reactive control of the slip velocity in comparison to the (indirect) treadmill training (A_S1 vs. B_S16, $p<0.001$, Fig. 5a). However, the direct training's impact on further improving the control of limb support was rather limited (A_S1 vs. B_S16, $p>0.05$, Fig. 5f).

Discussion

The present study has, for the first time, demonstrated the success of a treadmill-training protocol that was designed to augment movement error, while still allowed subjects to follow a progressive, error-reduction adaptive process similar to that observed in a repeated-slip training paradigm (Pai and Bhatt, 2007; Pai et al., 2010). Fall-resisting skills acquired from such training indeed successfully transferred to over-ground walking by reducing young adults' risk of falls upon their first, novel slip. Such reduction in fall risk resulted from the generalized improvements in the control of stability (both proactive and reactive). Although the *direct* training from repeated over-ground-slips could further improve the control of stability in over-ground walking, the *indirect* training obtained from treadmill-slips was still *sufficient* to eliminate any slip-related falls outside of the training environment.

Our results supported Hypothesis One: following their treadmill training, subjects in Group A successfully reduced their likelihood of falls upon the unannounced, novel slip during over-ground walk. Such reduction resulted from the modification in these subjects' motor behavior before (proactive) and after (reactive) the slip onset. The treadmill training clearly affected the proactive control during unperturbed over-ground walking, that these subjects exhibited a greater COM stability by positioning their COM more anterior than did the control group. While keeping the same step length and gait speed, they adopted flatfoot landing (with an average change of 4.8 degrees) upon heel strike. This technique reduces one's reliance on floor friction for braking forward momentum when the slip occurs, thereby reducing the peak slip velocity the subject experiences during the slip (Bhatt et al., 2006; Chambers and Cham, 2007).

While proactive control resulted primarily from feed-forward mechanisms, the reactive control could be influenced by both feed-forward and feedback mechanisms, such as spinal reflex or supraspinal automatic postural response (Diener et al., 1988). Generalization was also evident in reactive control of COM stability by further shifting the COM anteriorly and reducing slip (BOS) velocity. Reduction in BOS velocity was achieved by continued decrease in the demand on friction after the flatfooted landing through moderating the push-off force generated by the trailing foot before its liftoff (Bhatt et al., 2006) and increasing the knee flexor moments of the slipping limb (Cham and Redfern, 2001; Yang and Pai, 2010). As such, adaptive improvement from indirect training was similar to that observed in direct training albeit at a lesser degree (Fig. 5).

Controlling stability and providing adequate limb support against gravity are the two essential elements of fall-resisting skills, together they can account for 100% of the variability in falls (Yang et al., 2011). Insufficient limb support (a deficit proportionate to the reduction in the amount of upward impulse generated by ground reactive force), as characterized by excess hip descent upon recovery foot touchdown, could result in a fall (Yang et al., 2009). As we hypothesized, *direct* training did yield significantly better reactive control of COM position and the slip velocity than did *indirect* training (Fig. 5a, c). The difference in the amount of improvement that direct and indirect training appeared to yield on limb support was not significant (Fig. 5f), however. If limb support was sufficient in the studied cases, this could explain why no subjects fell in the post-treadmill-training trial of A_S1, although Group B displayed even better reactive control of COM stability than did Group A.

The CNS apparently updated and modified its motor program in response to elevated threats of postural perturbation. Past studies have demonstrated adaptation to over-ground moveable platform slips within 3 to 5 trials (Bhatt et al., 2006). Subjects who underwent treadmill-slip training were unable to adapt successfully (without taking a recovery step in three or more out of five trials) in their reaction to a comparable initial perturbation intensity (slip distance: 0.24m ; acceleration: 12m/s^2), although they were eventually successful at a lower perturbation level (Fig. 3). These differences can be accounted for by the differences in how a slip was induced. In the treadmill-slip training, the slip velocity was dictated by a pre-programmed servomotor that could not be altered by the subjects (Fig. 2c–d). Conversely, those who received over-ground-slip training could learn through their active control of slip velocity (Fig. 5a). The current treadmill slip protocol was designed to mitigate such a limitation and to mimic the natural progression of adaptation. After allowing subjects to experience augmented movement error, this was achieved by systematically reducing the perturbation intensity to ensure that they also received successful learning experience.

The training protocol explored in the present study is only one of many options that may yield training effects to successfully mitigate fall-risk. The present study merely represents an early attempt to simulate the spontaneous adaptive process observed in over-ground-slip training on a computer-controlled treadmill. Our intention was to optimize stimulus-response properties of training effects. Because this is the first study of its kind, only healthy (no neurological musculoskeletal or other systemic disorder) young participants were included to reduce the risk of potential injury that can be caused by such large-scale perturbation to population with high risk of fracture. It is unclear how these results may change with a different population (like older adults or individuals with movement disorders). Further, the full scope dose-response characteristics and its relationship with generalization or with retention are still unknown. It is perceivable that both effects may reduce if the initial training intensity is reduced. Previous work has investigated such dose-response in young adults which indicated that a single session of 24 slips was robust for retention of training effects over a period of 4 months in comparison to a control group receiving only single-slip (Bhatt and Pai, 2009). Such training intensity alteration is also expected to have an effect on generalization, which has been previous investigated across different context (Bhatt and Pai, 2009; Prakriti and Lockhart, 2012). While charting the dose-response from such treadmill training and relating it to retention and to generalization are far beyond the scope of the present study, they certainly warrant further investigation.

Despite its limitations, training on treadmill is highly desirable. Treadmill-based training facilities are versatile and portable and can therefore overcome space limitations imposed by clinics and community centers. Treadmill training protocol can be highly standardized and reproducible because, to a great extent, a clinician can easily and precisely control the perturbation int ensity. It is also conceivable that a portable treadmill-training device could fit in a vehicle to provide a *mobile service*.

In summary, the treadmill-slip training was able to achieve its primary objective of reducing the likelihood of falls upon a novel slip during over-ground walking. Such reduction resulted from the improvements in the control of dynamic stability, both proactive and reactive. These findings may call for a new paradigm, to be used in conjunction with volitional-performance-based training (Carter et al., 2001; Shumway-Cook et al., 1997); an adaptive perturbation training that enables older adults to learn from falling (*i.e.*, from making gross movement error) (Pai and Bhatt, 2007).

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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References

Baker SP, Harvey AH. Fall injuries in the elderly. Clinics in Geriatric Medicine. 1985; 1:501–512. [PubMed: 3913506]

Bhatt T, Pai Y-C. Immediate and latent interlimb transfer of gait stability adaptation following repeated exposure to slips. Journal of Motor Behavior. 2008; 40:380–390. [PubMed: 18782713]

Bhatt T, Pai Y-C. Generalization of gait adaptation for fall prevention: from moveable platform to slippery floor. Journal of Neurophysiology. 2009; 101:948–957. [PubMed: 19073804]

Bhatt T, Wening JD, Pai Y-C. Adaptive control of gait stability in reducing slip-related backward loss of balance. Experimental Brain Research. 2006; 170:61–73.

Bhatt T, Yang F, Pai Y-C. Learning to resist gait-slip falls: long-term retention in community-dwelling older adults. Archive of Physical Medicine and Rehabilitation. 2012; 93:557–564.

Boardman K, AI-Jaward M, Biriggs L, Kendrick D. Falls assessment and prevention: a multidisciplinary teaching intervention. The Clinical Teacher. 2010; 7:206–210. [PubMed: 21134185]

Cakit BD, Saracoglu M, Genc H, Erdem HR, Inan L. The effects of incremental speed-dependent treadmill training on postural instability and fear of falling in Parkinson's disease. Clinical Rehabilitation. 2007; 21:698–705. [PubMed: 17846069]

Carter ND, Kannus P, Khan KM. Exercise in the prevention of falls in older people: a systematic literature review examining the rationale and the evidence. Sports Medicine. 2001; 31:427–438. [PubMed: 11394562]

Cham R, Redfern MS. Lower extremity corrective reactions to slip events. Journal of Biomechanics. 2001; 34:1439–1445. [PubMed: 11672718]

Chambers AJ, Cham R. Slip-related muscle activation patterns in the stance leg during walking. Gait and Posture. 2007; 25:565–572. [PubMed: 16876417]

de Leva P. Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. Journal of Biomechanics. 1996; 29:1223–1230. [PubMed: 8872282]

Diener HC, Horak FB, Nashner LM. Influence of stimulus parameters on human postural responses. Journal of Neurophysiology. 1988; 59:1888–1905. [PubMed: 3404210]

Hakim RM, Roginski A, Walker J. Comparison of fall risk education methods for primary prevention with community-dwelling older adults in a senior center setting. Journal of Geriatric physical Therapy. 2007; 30:60–68. [PubMed: 18171489]

Hu MH, Woollacott MH. Multisensory training of standing balance in older adults: II. Kinematic and electromyographic postural responses. Journal of Gerontology. 1994; 49:M62–M71. [PubMed: 8126354]

Kessenich CR. Tai Chi as a method of fall prevention in the elderly. Orthopaedic Nursing. 1998; 17:27–29. [PubMed: 9814334]

Luukinen H, Herala M, Koski K, Honkanen R, Laippala P, Kivela SL. Fracture risk associated with a fall according to type of fall among the elderly. Osteoporosis International. 2000; 11:631–634. [PubMed: 11069199]

Mansfield A, Peters AL, Liu BA, Maki BE. Effect of a perturbation-based balance training program on compensatory stepping and grasping reactions in older adults: a randomized controlled trial. Physical Therapy. 2010; 90:476–491. [PubMed: 20167644]

Pai Y-C, Bhatt T. Repeated slip training: An emerging paradigm for prevention of slip-related falls in older adults. Physical Therapy. 2007; 87:1478–1491. [PubMed: 17712033]

Pai Y-C, Bhatt T, Wang E, Espy D, Pavol MJ. Inoculation against falls: rapid adaptation by young and older adults to slips during daily activities. Archive of Physical Medicine and Rehabilitation. 2010; 91:452–459.

Prakriti P, Lockhart TE. Effects of moveable platform training in preventing slip-induced falls in older adults. Annals of Biomedical Engineering. 2012; 40:1111–1121. [PubMed: 22134467]

Rubenstein LZ, Josephson KR. Falls and their prevention in elderly people: what does the evidence show? Medical Clinics of North America. 2006; 90:807–824. [PubMed: 16962843]

Shimada H, Obuchi S, Furuna T, Suzuki T. New intervention program for preventing falls among frail elderly people: the effects of perturbed walking exercise using a bilateral separated treadmill. American Journal of Physical Medicine and Rehabilitation. 2004; 83:493–499. [PubMed: 15213472]

Shumway-Cook A, Gruber W, Baldwin M, Liao S. The effect of multidimensional exercises on balance, mobility, and fall risk in community-dwelling older adults. Physical Therapy. 1997; 77:46–57. [PubMed: 8996463]

Tideiksaar R. Fall prevention in the home. Topics in Geriatric Rehabilitation. 1987; 3:57–64.

Tinetti ME. Preventing falls in elderly persons. The New England Journal of Medicine. 2003; 388:42–49. [PubMed: 12510042]

Tinetti ME, Baker DI, McAvay G, Claus EB, Garrett P, Gottschalk M, Koch ML, Trainor K, Horwitz RI. A multifactorial intervention to reduce the risk of falling among elderly people living in the community. New England Journal of Medicine. 1994; 331:821–827. [PubMed: 8078528]

Wolf SL, Sattin RW, Kutner M, O'Grady M, Greenspan AI, Gregor RJ. Intense Tai Chi exercise training and fall occurrences in older, transitionally frail adults: a randomized, controlled trial. Journal of American Geriatrics Society. 2003; 51:1693–1701.

Woollacott MH, Tang PF. Balance control during walking in the older adult: Research and its implications. Physical Therapy. 1997; 77:646–660. [PubMed: 9184689]

Yang F, Anderson FC, Pai Y-C. Predicted threshold against backward balance loss following a slip in gait. Journal of Biomechanics. 2008a; 41:1823–1831. [PubMed: 18538329]

Yang F, Bhatt T, Pai Y-C. Role of stability and limb support in recovery against a fall following a novel slip induced in different daily activities. Journal of Biomechanics. 2009; 42:1903–1908. [PubMed: 19520372]

Yang F, Bhatt T, Pai Y-C. Limits of recovery against slip-induced falls while walking. Journal of Biomechanics. 2011; 44:2607–2613. [PubMed: 21899844]

Yang F, Pai Y-C. Correction of the inertial effect resulting from a plate moving under low-friction conditions. Journal of Biomechanics. 2007; 40:2723–2730. [PubMed: 17306274]

Yang F, Pai Y-C. Role of individual lower limb joints in reactive stability control following a novel slip in gait. Journal of Biomechanics. 2010; 43:397–404. [PubMed: 19896133]

Yang F, Pai Y-C. Automatic recognition of falls in gait-slip training: Harness load cell based criteria. Journal of Biomechanics. 2011; 44:2243–2249. [PubMed: 21696744]

Yang F, Passariello F, Pai Y-C. Determination of instantaneous stability against backward balance loss: Two computational approaches. Journal of Biomechanics. 2008b; 41:1818–1822. [PubMed: 18405903]

York SC, Shumway-Cook A, Silver IF, Morrison AC. A Translational Research Evaluation of the Stay Active and Independent for Life (SAIL) Community-Based Fall Prevention Exercise and Education Program. Health Promotion Practice. 2011; 12:832–839. [PubMed: 21191079]

Yungher DA, Morgia J, Bair WN, Inacio M, Beamer BA, Prettyman EG, Rogers MW. Short-term changes in protective stepping for lateral balance recovery in older adults. Clinical Biomechanics. 2012; 27:151–157. [PubMed: 22000701]

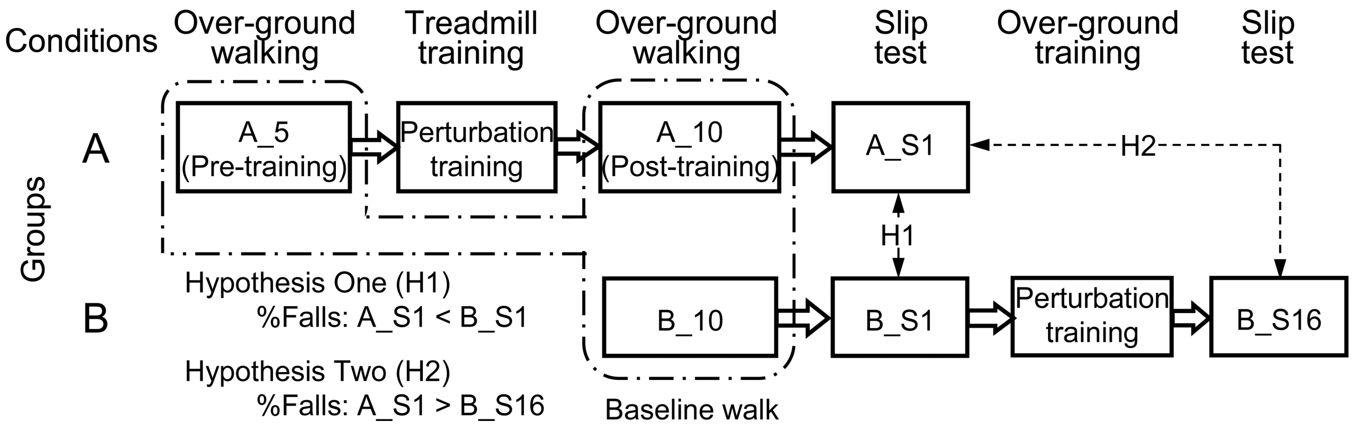

Fig. 1.

Schematics of study design to test the transfer of treadmill-training effect. Group A (treadmill-slip-training group) took five trials of spontaneous (and unperturbed) over-ground walk (pre-training baseline trials, from A_1 to A_5) before receiving a minimum of 15 "slip-like" perturbation trials on treadmill. After the treadmill training, these subjects then took another five trials of spontaneous walk (post-training baseline trial, from A_6 to A_10), that were finally followed by an over-ground-slip trial (A_S1). Group B (over-ground-slip-training group) took ten baseline trials (from B1 to B10), followed by a block of eight over-ground slip trials (from B_S1 to B_S8), three non-slip trials, and eight more slips (B_S9 to B_S16). Because both first over-ground slips, A_S1 and B_S1, were equally novel in which subjects did not know when, where, or how a slip could occur, B_S1 served as the control for A_S1 to test Hypothesis One (H1: treadmill training reduces likelihood of falls in over-ground slip). B_S16 represented the post-training trial for over-ground-slip training. The comparisons between A_S1 and B_S16 were used to examine Hypothesis Two (H2: direct over-ground-slip training has greater fall reduction effect than does indirect treadmill-slip training)

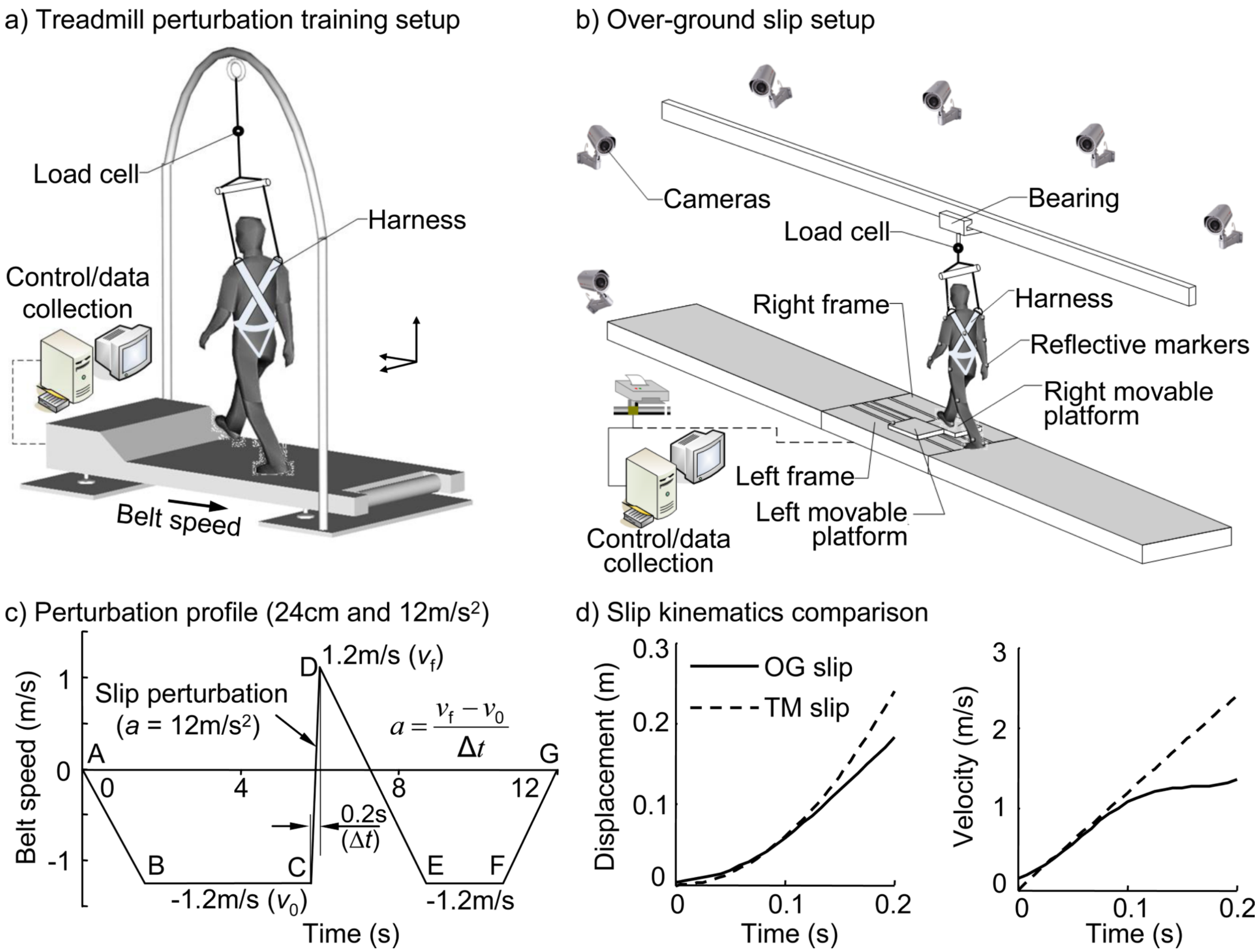

Fig. 2.

Schematics of a) the treadmill used to produce slip-like perturbation, b) the over-ground walkway and the movable platforms, c) the profile of the treadmill perturbation for a slip trial with an acceleration of 12 m/s^2 and a displacement of 0.24 m, and d) the comparison of the displacement-velocity profile between Group A's treadmill slip at its beginning perturbation level of 12 m/s^2 (TM, broken line, corresponding to the section between time instants C and D in Fig. 2c) and a sample trial from Group B's first novel over-ground slip (OG, solid line). In each treadmill-slip trial, the top belt would suddenly accelerate and thus abruptly reduce its backward speed, causing an equivalent forward slip perturbation. The perturbation occurred about four to ten steps after the belt ramped up to its steady speed of −1.2 m/s (negative means moving backward), then quickly accelerated to 1.2 m/s within 0.2 s. Following the perturbation, the belt speed returned to −1.2m/s. A slip in over-ground walking was induced by the release of two side-by-side low-friction movable platforms. Each of the two platforms was firmly locked in baseline trials, resting on a frame with four linear bearings. The frame was bolted to two force plates to measure the ground reaction force (these structures are not shown here and invisible from the walkway). The low-profile movable platforms were embedded in a 7-m instrumented walkway along with decoy platforms (not shown). They were unlocked without the knowledge of the subject through the control of computer after the touchdown of the corresponding foot during a slip trial.

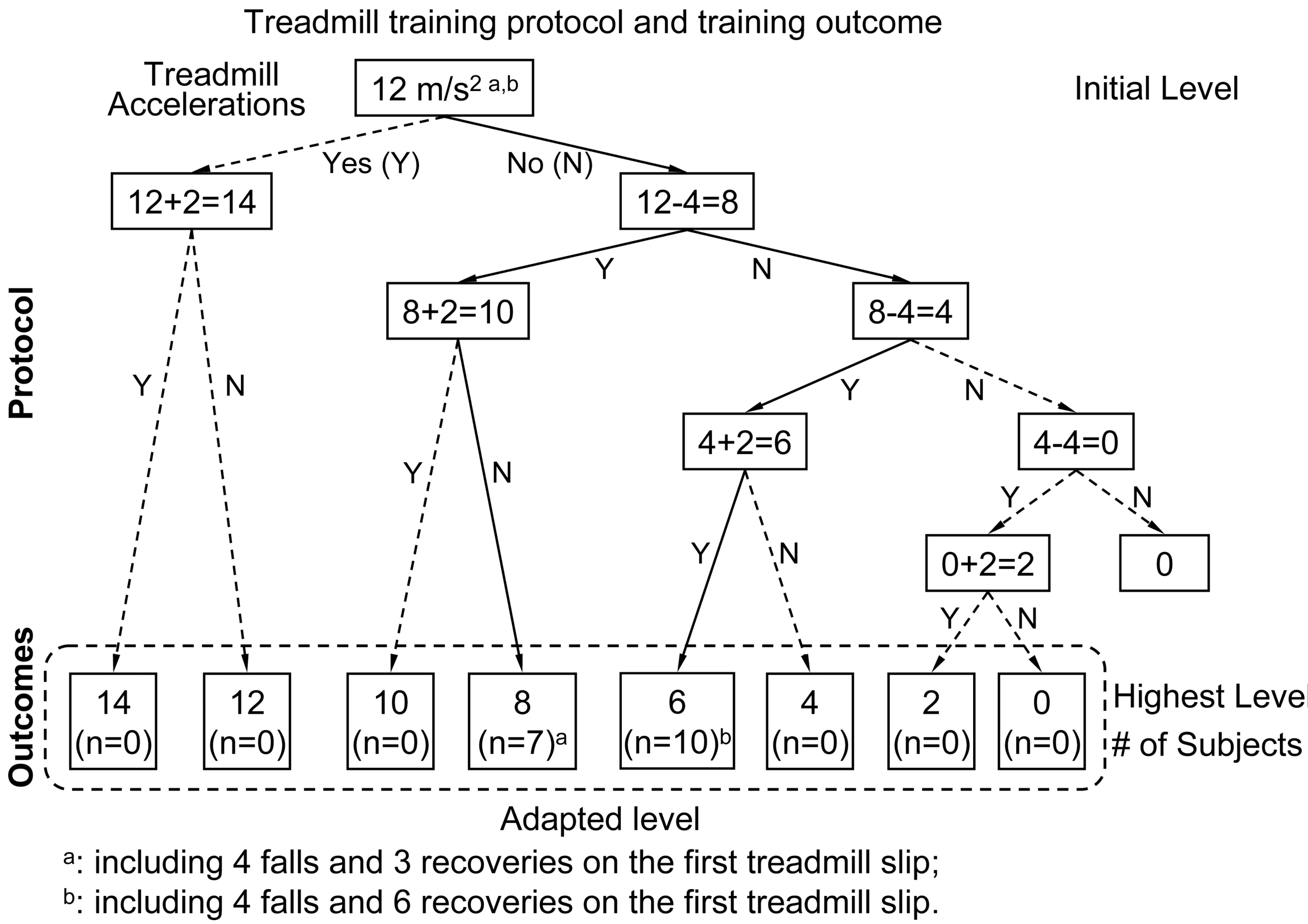

Fig. 3.

Treadmill training protocol and outcomes. The beginning perturbation level was an acceleration of 12 m/s^2 (Fig. 2c). When subject adapted successfully without landing the recovery foot posterior to the slipping foot in at least three out of those five trials ("Yes" or "Y"), the next perturbation level would go up by an increment of 2 m/s^2 for another five trials. Otherwise ("No" or "N") the perturbation level would decrease by a decrement of 4 m/s^2. All possible outcomes are displayed in the dashed box. The numbers in the parentheses are the actual number of the subjects who adapted successfully at their corresponding highest perturbation level. The solid arrow indicates the adapted level that actually occurred in the training process; while the dashed arrow represents the possible perturbation level that never occurred during the actual training.

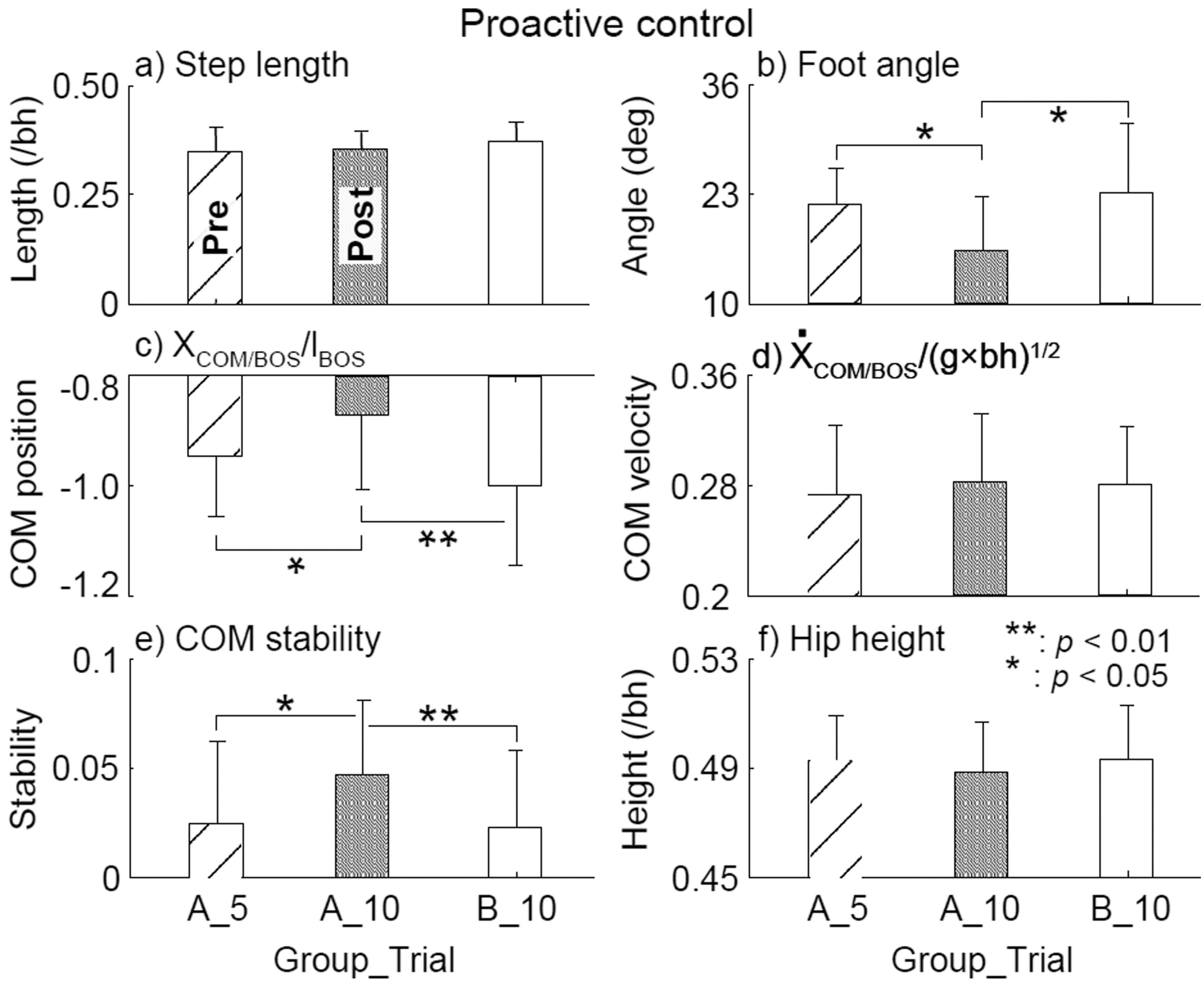

Fig. 4.

Comparisons of a) step length, b) foot angle, c) the center of mass (COM) position, d) COM velocity, e) COM stability, and f) hip height between the treadmill-slip training group (Group A, $n = 17$) and the over-ground-slip training group (Group B, $n = 17$). Because these measurements are taken at right foot touchdown during their baseline (unperturbed walking) trials, before (Pre) and after (Post) Group A's treadmill training (A_5 and A_10) and before Group B's first slip trial (B_10), they are reflective of the proactive.

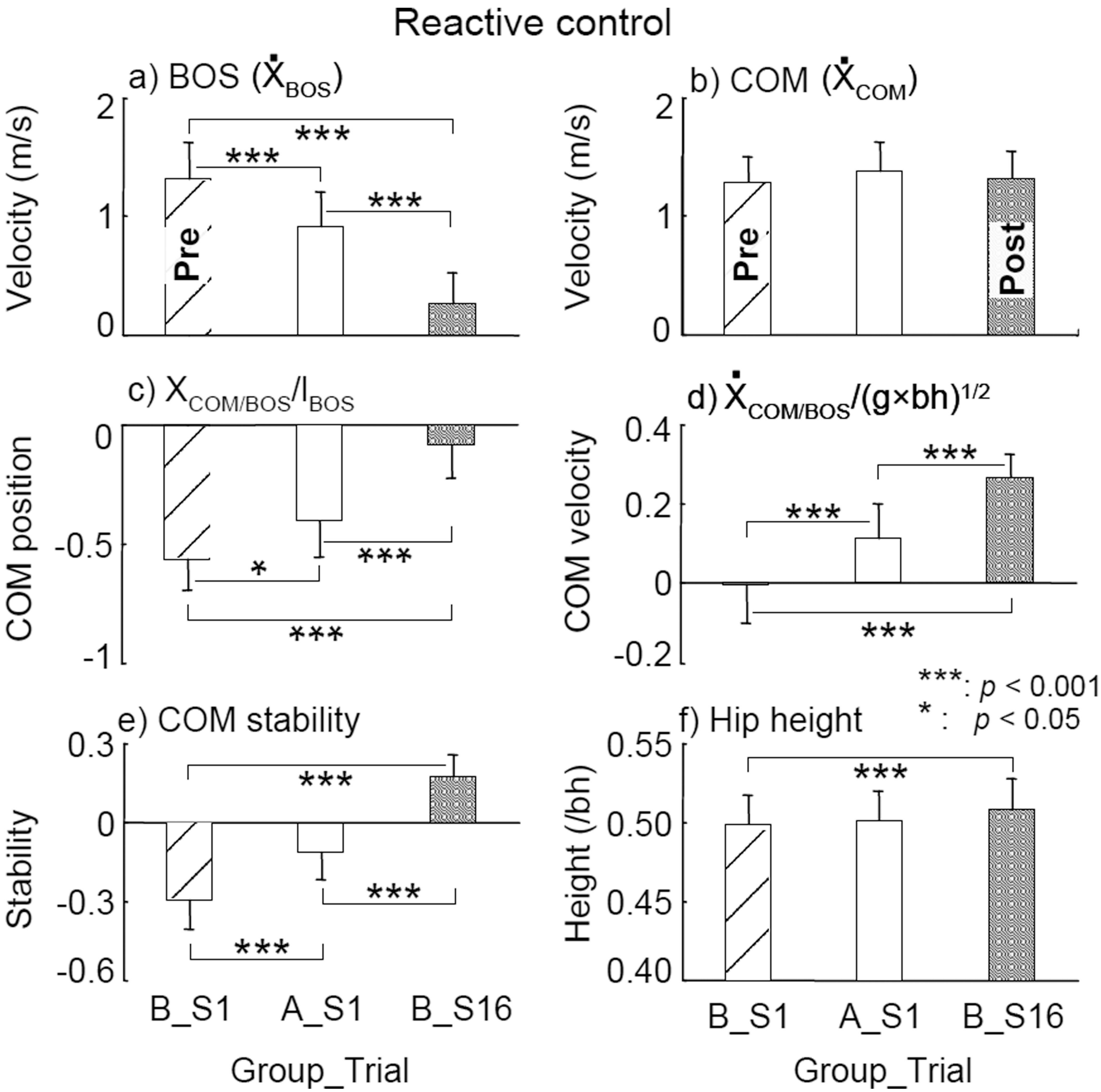

Fig. 5.

Comparisons of a) the absolute base of support (BOS) velocity, b) the absolute COM velocity, c) the relative COM position, d) the relative COM velocity, e) COM stability, and f) the hip height during Group B's first (B_S1) and 16th (B_S16) slip trial and Group A's first (A_S1) slip trial during over-ground walking. Because these measurements are taken at recovery foot liftoff approximately 150 ms after the slip onset, they are reflective of the reactive control. The first slip was completely novel to all subjects in Groups A and B, who did not know how, when or where it would occur. Group B's B_S1 (Pre) training was therefore served as the control trial to A_S1, which took place after Group A's treadmill training. Group B's 16th slip trial (B_S16) was included here to assess the (Post) training effect from repeated slips induced during over-ground walking.

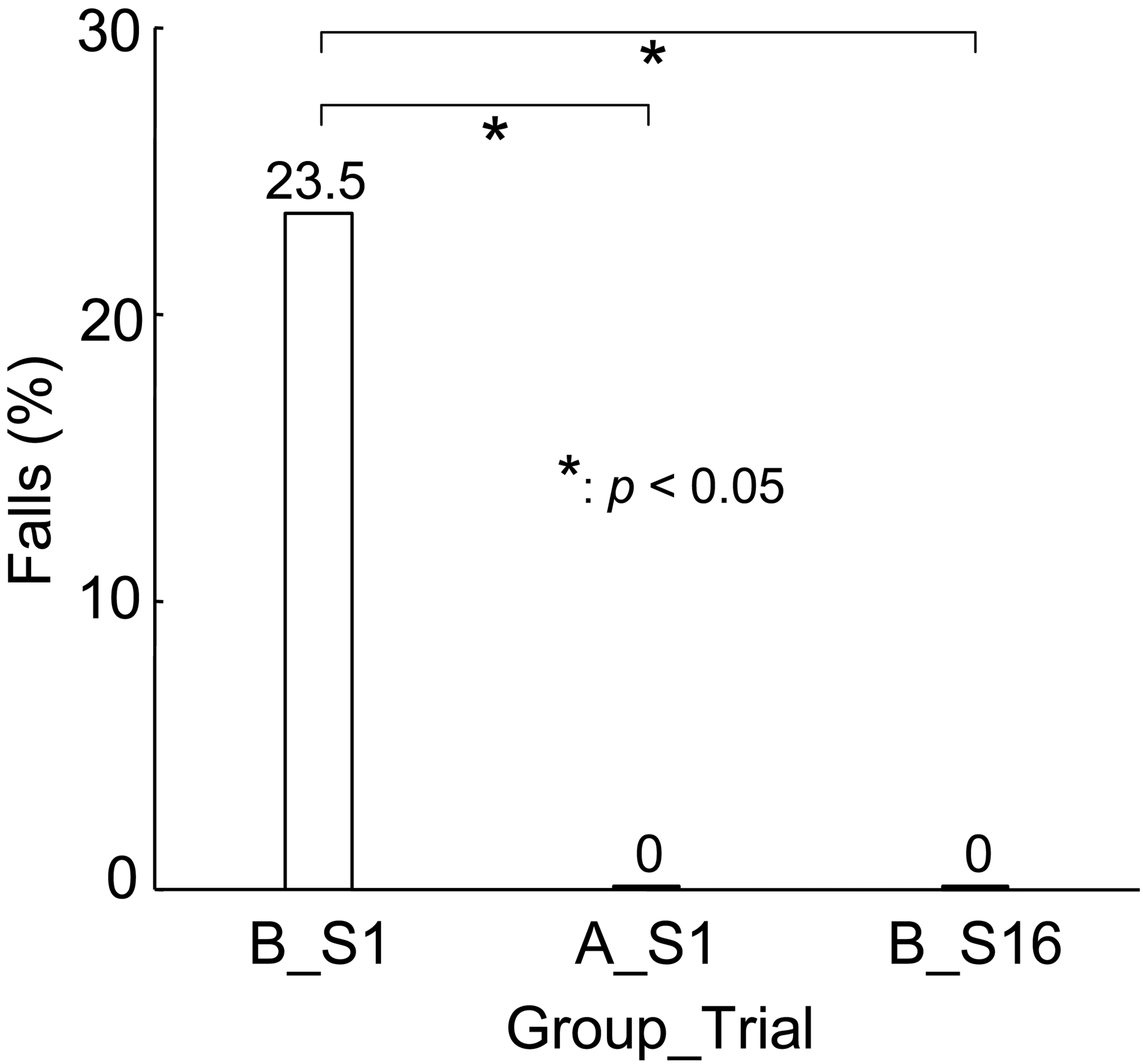

Fig. 6.
Comparison of fall incidence (%) resulting from the first, novel over-ground slip between the treadmill-slip training group (Group A, $n = 17$, A_S1) and the over-ground-slip training group (Group B, $n = 17$, B_S1), and after their repeated-slip exposure, from Group B's 16th slip (B_S16).

Table 1

The demographics in mean ± SD for treadmill-slip training group (Group A) and over-ground-slip training group (Group B).

Groups	Gender (female)	Age (years)	Height (m)	Mass (kg)
A (*n* = 17)	7	24.5 ± 4.9	1.69 ± 0.09	63.8 ± 14.2
B (*n* = 17)	9	27.1 ± 5.3	1.70 ± 0.07	69.1 ± 10.5

Table 2

Slip kinematics (mean ± SD) of the first, novel slip recorded as the control trial during Group B's (*n* = 17) over-ground walking and different training intensity levels applied to Group A (*n* = 17) during its treadmill-slip training that all began at the level of $12 m^2/s$.

Groups	Acceleration (m/s^2)	Slip velocity[a] (m/s)	Slip distance (cm)	Duration[b] (s)
A	12	2.4	24	0.2
	10	2.0	20	0.2
	8	1.6	16	0.2
	6	1.2	12	0.2
B	15.3 ± 5.4[c]	2.19 ± 0.64[c]	61.6 ± 32.2[c]	0.63 ± 0.30[c]
	7.3 ± 6.9[d]	1.65 ± 0.43[d]	26.4 ± 9.5[d]	0.31± 0.05[d]

[a]For Group A, calculated as the difference of the belt speed between instants of C and D in Fig. 2c;

[b]For Group A, the duration between instants of C and D in Fig. 2c;

[c]The peak values during the slip;

[d]The values at the instant of the recovery (left) foot touchdown after slip onset.