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Reduced intensity in gait-slip training can still improve stability

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ABSTRACT

Perturbation training with "free" slips (i.e., with long slip distance) has been able to successfully improve stability and to reduce the incidence of falls among older adults. Yet, it is unclear whether a highly constrained training with reduced slip distance (and hence training intensity) can achieve similar effects. The purpose of this study was to investigate whether short-distance slips could also improve the control of stability, and whether such improvements could be generalized to a novel, "free" slip. Thirty-six young subjects were randomly assigned to either one of the two training groups, which underwent seven training trials with constrained slips of either 12-cm or 18-cm in distance before encountering a novel, "free" slip (up to 150 cm) in the test trial; or the control group, which only experienced the same test trial of a novel, "free" slip. The results showed that while both training groups were able to significantly improve their control of stability in training; the 18-cm group had significantly better reactive control of stability than the 12-cm group. During the "free" slip, such advantage enabled the 18-cm group to exhibit significantly less balance loss incidence than 12-cm group (58.3 vs. 83.3%) and the controls (100%). These differences could be fully accounted for when we assume that the central nervous system directly controls slip velocity or slip distance during adaptation, whereby the level of similarity between training trials and the test trial governs the degree of generalization. The findings that low intensity training may still improve stability warrant further investigations among older adults.

1. Introduction

Falls are among the most serious problems facing older adults, which can cause injuries and even death (Nyberg et al., 1996). Slips comprise 40% of outdoor falls among older adults (Luukinen et al., 2000). Therefore an effective training program to prevent slip-related falls is highly desired. An emerging paradigm relies on perturbation training to reduce fall-risk (Bhatt et al., 2006; Parijat and Lockhart, 2012; Shimada et al., 2004). Repeated-slip exposure, for instance, forces the central nervous system (CNS) to adopt proactive (feed-forward) and reactive control strategies that, even if unconscious, can improve the control of the center of mass (COM) stability relative to the slipping base of support (BOS), and consequently lead to the reduction in the likelihood of falls. Such training-induced adaptive changes can reduce laboratory-induced fall incidence by nearly 50% among older adults (Pai et al., 2010).

While these results are very promising, inducing slips-and-falls might be of some concern among frail elderly or those who are not in physical conditions to tolerate such training. The first novel slip can travel up to 0.7 m (Yang and Pai, 2007) at a peak speed of 2.51 m/s (Yang et al., 2009). It is unknown whether and to what degree that repeated slips with short-distance (constrained) could still elicit training adaptation and the generalization of such training effects to a different context upon encountering a novel and "free" slip in real-life. Logically, low intensity training with shorter slip distance and lower peak slip velocity could be more conducive and likely safer among frail older adults.

The purpose of this study was, therefore, to investigate whether short-distance slips could also improve the control of stability, and whether such improvements could be generalized to a novel, "free" slip. Two training groups first underwent training with short-distance slips (12-cm or 18-cm), and were then exposed to a novel, unconstrained, "free" slip with a maximum allowable slip distance up to 150 cm. We hypothesized that both training groups could generalize the improved response to the "free" slip in comparison to the control group's response to the same "free" slip. Because 18-cm slip would have closer resemblance to the "free" slip than did the 12-cm slip, we also expect the former group will perform better than did the latter during slip recovery upon the novel "free" slip.

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2. Methods

2.1. Subjects and experimental setup

Thirty-six healthy young adults (24.9 ± 3.7 years) participated in the institutionally approved study (Table 1). Unexpected slip perturbations were induced as subjects walked along a 7-m walkway in which a sliding device was embedded (Fig. 1a). The device consisted of a pair of low-friction, passively movable platforms each mounted upon a metal frame supported by two individual force plates (AMTI, Watertown, MA) for recording the ground reaction force (Yang and Pai, 2007). Only the right platform was used to induce slip in the present study. Once released on slip trials, the platform was "free" to smoothly slide forward up to 1.5 m without the stoppers installed on the tracks. During the training, the stoppers were installed along these tracks to reduce the slip distance under the constrained conditions. The platform release was automatically achieved by a computer-controlled program. All subjects wore a safety harness, which was linked through a load cell to a ceiling-mounted beam during walk (Fig. 1a).

2.2. Experimental protocol

Subjects were randomly and evenly assigned to three groups: two training groups and a control group. Subjects in both training groups received slip training with reduced slip distances before exposed to a "free" slip; while the control group only experienced the "free" slip without any training (Fig. 1b). One of the training groups experienced slips with maximum distance of 12 cm during the training session (the 12-cm group), while the other experienced slips with maximum distance of 18 cm (the 18-cm group). Other than the different maximum slip distance (12 or 18 cm), the training protocols were identical between these two groups (Fig. 1b). Subjects were informed that they would be performing normal walking initially and would experience simulated slips later without knowing when, where, and how that would happen. They were also told to try to recover their balance on any slip incidence and then to continue walking forward. A slip was induced on the ninth trial, which was followed by four consecutive slip trials, a block of three nonslips, and the second block of two re-slips for a total seven slips (S1–S7). Finally, after another five trials of unperturbed walking, they experienced the unconstrained slip test (ST). The subjects in the control group received the same instruction while they only experienced the ST after eight unperturbed trials (Fig. 1b).

2.3. Data collection

Full body kinematic data from 28 retro-reflective markers placed on the subjects' body and platforms were gathered using an 8-camera motion capture system (MAC, Santa Rosa, CA) at 120 Hz. Marker paths were low-pass filtered at marker-specific cut-off frequencies (ranging from 4.5 to 9 Hz) using fourth-order, zero-lag Butterworth filters (Winter, 2005). Force plate and load cell data were collected at 600 Hz and synchronized with motion data. Three dimensional locations of joint centers, heels, and toes were computed from the filtered marker positions.

2.4. Trial outcomes, events, and kinematic variables

A fall was classified when the peak load cell force during slip exceeded 30% body weight; while a recovery was identified if the moving average load cell force did not exceed 4.5% body weight over any 1-s period after slip onset (Yang and Pai, 2011). When the recovery heel landed posterior to the slipping heel after the slip onset, the trials would be classified as backward balance loss trials. Conversely, trials with the recovery heel landing anterior to the slipping heel were classified as no balance loss trials (Bhatt et al., 2006). The events of interest included the instant of the slipping (right) limb touchdown (RTD), the instant of the recovery (left) limb liftoff (LLO), and the instant immediately prior to its touchdown (LTD). These events were determined from the vertical ground reaction force.

The body COM kinematics was calculated using a 13-segment rigid body model (de Leva, 1996). 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. The COM stability was evaluated by calculating the shortest distance from the COM motion state to the limits against backward balance loss (Fig. 2) (Yang et al., 2008a, 2008b). Preslip stability was obtained at RTD; post-slip stability was obtained at the instants of LLO and LTD.

Several gait variables including preslip step length and foot angle, and BOS velocity at LLO were calculated to further understand the contributing factors to adaptive changes in the stability. Preslip step length was calculated as the anteroposterior distance measured between both heel markers at RTD. Foot angle was the angle between the sole and ground and was calculated at RTD. The BOS velocity at LLO was the platform's speed at the instant of LLO. In addition, the peak BOS velocity and the maximum BOS travel distance were also analyzed for slip trials. The peak BOS velocity was calculated as the maximum BOS travel velocity during the slip. The maximum BOS travel distance was the longest forward displacement of the BOS during the period of the right stance phase. These variables were computed upon S1 and S7 for training groups; and upon ST for all groups.

To examine the differences of the slip training between two training groups, the following three additional variables characterizing the BOS kinematics were also analyzed upon the training slips for both groups. They included the travel distance of the platform from RTD to the instant of the peak BOS velocity ($X_{BOS,T_{peak},V_{BOS}}$), the time instant when peak BOS velocity was reached relative to LLO ($T_{peak,V_{BOS}}$), and the time instant when maximum BOS displacement achieved ($T_{max,X_{BOS}}$). These variables were calculated on S1 and S7 for training groups. The improvements in the COM stability, the landing kinematics, and the BOS slip kinematics from S1 to S7 were calculated as the difference of these variables between trials for both groups.

2.5. Statistics

To assess demographic and age differences between three different groups, these variables were compared across all three groups using a one-way analysis of variance (ANOVA) (factor: group, 12-cm vs. 18-cm vs. control). The generalized estimating equation (GEE) test, post-hoc Wilcoxon Signed-Rank test, and Mann Whitney test were applied to examine the training effect on backward balance loss reduction in each training group (the within-group factor: S1 vs. S7), and to examine the similarity of training effect across both training groups (the between-group factor: 12-cm vs. 18-cm). In parallel, ANOVA for repeated measures, with group (12-cm vs. 18-cm) as between group factor and trial (S1 vs. S7) as the within group factor was used to assess adaptive improvements in time elapsed during the single and double stance phase after slip onset, the stability control, preslip step length, preslip foot angle, BOS velocity at LLO, and BOS kinematics. Significant main effects and interactions were resolved with paired and independent t-tests using the proper corrections. The improvements in COM stability, BOS kinematics, and the landing kinematics were compared between groups (12-cm vs. 18-cm) using independent t-tests.

To investigate issues related to the generalization, χ^2 tests were performed to compare the backward balance loss incidence on ST among all three groups. Generalization effects were evaluated first by comparing the slip outcome and later by examining both proactive (preslip) and reactive (post-slip) control in slip responses. One-way ANOVAs (factor: group) with Tukey's post-hoc tests were conducted to compare the differences among the three groups upon the ST slip in the following variables: durations of the single and double stance phases, the pre- and post-slip stability, the preslip step length and foot angle, BOS velocity at LLO, peak BOS velocity, and maximum BOS displacement. All analyses were performed using SPSS 19 (IMB Corp., Armonk, NY) with a significance level of 0.05.

Table 1
The demographics in mean ± SD for two training groups (12-cm and 18-cm) and the control group.

Groups	12-cm (n=12)	18-cm (n=12)	Control (n=12)	p value	Pooled (n=36)
Age (years)	24.4 ± 3.2	23.6 ± 3.4	26.6 ± 4.0	0.12	24.9 ± 3.7
Height (cm)	169.7 ± 8.0	170.8 ± 6.3	174.8 ± 7.2	0.20	171.8 ± 7.3
Mass (kg)	64.2 ± 8.4	68.0 ± 8.0	69.6 ± 11.1	0.36	67.3 ± 9.3
Sex (female)	6 (50.0%)	7 (58.3%)	10 (83.3%)	0.21*	23 (63.9%)

* χ^2 test was used.

3. Results

3.1. Adaptation to slip training

Although more subjects in the 18-cm group experienced backward balance loss on the first training slip (S1) than the 12-cm group (91.6% vs. 58.3%, p=0.059, Fig. 3), both groups were able to significantly reduce incidence of balance loss at the end (S7) of training (0% for the 18-cm group, and 8.3% for the 12-cm group; p < 0.001 within group, p=0.204 between group, and group-by-trial interaction: p=0.012, Fig. 3). The significant group-by-trial interaction indicated that the

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