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Intensity and generalization of treadmill-slip training: high or low; progressively-increase or -decrease?

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ABSTRACT

Very little is known how training intensity interacts with the generalization from treadmill-slip to overground slip. The purposes of this study were to determine whether treadmill-slip training can improve center-of-mass stability, more so in the reactive than in the proactive control of stability, with high intensity (HI with a trial-to-trial-consistent acceleration of 12 m/s^2) better than low intensity training (LO with a consistent acceleration of 6 m/s^2) against overground slip; and whether progressively-increasing intensity (INCR with a block-to-block acceleration varied from 6 to 12 m/s^2) was better than progressively-decreasing intensity training (DECR with an acceleration varied from 12 to 6 m/s^2) in such generalization. Thirty-six young subjects, evenly assigned to one of four (HI, LO, INCR, DECR) groups, underwent 24 treadmill-slips before their generalization test trial with a novel slip during overground walking. The controls (CTRL, $n=9$) from existing data only experienced the same novel overground slip without treadmill training but under otherwise identical condition. The results showed that treadmill-slip training did improved balance control on overground slip with a greater impact on subjects' reactive (44.3%) than proactive control of stability (27.1%) in comparison to the CTRL. HI yielded stronger generalization than LO, while INCR was only marginally better than DECR. Finally, the group means of these four displayed a clear ascending order from CTRL, LO, DECR, INCR, to HI. The results suggested that higher training intensity on treadmill led to a better generalization, while a progressively-increase in intensity had a slight advantage over the progressively-decrease strategy.

1. Introduction

Falling is the key precursor to the pathogenesis of hip fracture and a major cause of death in older adults (Hayes et al., 1996; Morley, 2002). Slip-related backward falls lead to 40% of falls among community-living adults and are particularly dangerous because they frequently cause hip fractures (Luukinen et al., 2000; Nevitt and Cummings, 1993). Learning through repeated perturbations (Bhatt et al., 2006a; Bieryla et al., 2007; Mansfield et al., 2010; Parijat and Lockhart, 2012) has become an emerging approach to improve the control of stability to reduce fall-risk.

Computer-controlled treadmill could be used to simulate slip-like perturbations for inducing adaptive effects on control of center-of-mass (COM) state stability and reducing fall-risk (Yang et al., 2013). The portability of the treadmill is well-suited for clinics and community centers, an advantage over the space occupying instrumented walkways required for overground training. To ensure that treadmill-slip training can reduce falls in everyday life, the generalization of treadmill-slip training to overground slip becomes essential. Also, during repeated overground-slip training (Bhatt et al., 2006b), a substantially greater improvements was found in post-slip onset (reactive) stability compared to pre-slip onset (proactive) stability. It is not determined whether this phenomenon would consist in generalization between two different but similar contexts. Another advantage of treadmill training is that the training intensities can be easily adjusted on the treadmill which provides us many training paradigm options. One could choose a high intensity and keep the training intensity in the highest level; or to start from the lowest intensity, and gradually reach the highest level and vice versa; or simply to start from the lowest intensity and conservatively stay at that easiest level. Among these many options, it is unclear which a desirable strategy is.

Higher training intensity could be more effective than lower training intensity in improving older adults' walking speed (van Ooijen et al., 2013). Higher perturbation intensity induced by medio-lateral translations of the treadmill platform led to a greater increase in margins of stability of young adults. This increase was found not only in medio-lateral direction, but also in

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backward direction hence indicative of a form of generalization (Hak et al., 2012). Other results also indicated that higher intensity in treadmill-slip training might have better training effects (Jayaram et al., 2011). On the other hand, very little is known about whether progressively-increasing or progressively-decreasing intensity training strategy can yield better generalization.

The purposes of this study were to determine whether (1) treadmill training improved stability, (2) treadmill training improved the reactive one more than the proactive control of stability, (3) high intensity treadmill-slip training (HI with a trial-to-trial-consistent acceleration of 12 m/s^2) was better than low intensity training (LO with a consistent acceleration of 6 m/s^2), and (4) progressively-increasing intensity training (INCR with a block-to-block acceleration varied from 6 to 12 m/s^2) was better than progressively-decreasing training (DECR with an acceleration varied from 12 to 6 m/s^2) in such generalization. We hypothesized that treadmill-slip training would improve control of stability on overground slip (Hypothesis 1), and possibly improve the reactive one substantially more than the proactive control of stability (Hypothesis 2). We further hypothesized that the HI would lead to a better generalization than the LO in the control of stability for slip recovery on overground walking (Hypothesis 3). We also expected INCR would be more effective than DECR (Hypothesis 4), because it follows the common practice in motor learning.

2. Methods

2.1. Subjects

Thirty-six young adults without histories of neurological, musculoskeletal and cardiopulmonary diseases participated in the treadmill-slip training study (Table 1). They were evenly assigned to four treadmill training groups (Fig. 1): high intensity training (HI) group, progressively-increasing intensity training (INCR) group, progressively-decreasing intensity training (DECR) group and low intensity training (LO) group. There were no significant differences in weight and height among groups. A control (CTRL) group (n=9) was adopted from previous studies (Bhatt et al., 2006b; Bhatt and Pai, 2008). This group received no treadmill perturbation training but underwent an otherwise identical novel slip. All subjects provided written informed consent. And this study was approved by Institutional Review Board in the University of Illinois at Chicago.

2.2. Study design

In the treadmill training groups, every subject first performed five regular walking trials as baseline trials on a 7-m overground walkway (Fig. 2b). After baseline trials, subjects in each treadmill group experienced different training paradigms (Fig. 1). Subjects in the HI and the LO group had 24 continuous slips with acceleration at 12 m/s^2 and 6 m/s^2, respectively. Subjects in the INCR and the DECR group received five blocks with a total of 24 slips. In the first three blocks, each had 6 repeated slips of the same acceleration (the block acceleration ranged from 6, 9 to 12 m/s^2 for INCR and 12, 9 to 6 m/s^2 for DECR). For the last two mixed blocks of three trials each, the acceleration within each block increased from 6 to 12 m/s^2 (INCR) or decreased from 12 to 6 m/s^2 (DECR). After the treadmill training, subjects went back to the same walkway for five walking trials before experiencing a novel overground slip. This slip served to test generalization of the training effects. Subjects were only told that they "may or may not" experience a slip in the trials. The slip was unannounced and unrehearsed. Subjects in the CTRL group received the same instruction. They only experienced a novel overground slip after ten walking trials (Fig. 1).

Table 1
The demographics in mean ± SD for the four treadmill training groups and the control group.

Groups	Age (years)	Height (m)	Mass (kg)	Sex (female)
HI (n=9)	23.3 ± 4.4	1.68 ± 0.07	63.2 ± 11.3	2
INCR (n=9)	25.4 ± 3.0	1.72 ± 0.07	68.0 ± 13.4	8
DECR (n=9)	25.8 ± 3.5	1.68 ± 0.07	62.2 ± 6.8	9
LO (n=9)	24.6 ± 3.8	1.69 ± 0.10	69.5 ± 24.3	4
CTRL (n=9)	26.7 ± 5.6	1.73 ± 0.08	68.3 ± 14.7	3

2.3. Experimental setup

The treadmill-slip training was conducted on ActiveStep treadmill (Simbex, Lebanon, NH) to simulate slips in walking (Fig. 2a). The training profiles were defined by ActiveStep software. The speed-time history of the treadmill belt for each training group was set before the experience. Each slip trial began with 2.5 s speed up, followed by a 5.5 s steady state with a backward-moving belt speed of 1.2 m/s. After 8–16 regular steps in each slip trial, the belt suddenly accelerated in the forward direction at the beginning of the next single stance phase. This mimicked a slip where the subject's base of support (BOS) moved forward relative to the COM (Yang et al., 2013) and the slip happened without the subjects' knowledge. After 0.2 s, the belt speed underwent a 2.4 s of backward acceleration to reach the same ending speed of 1.2 m/s in the backward direction. The magnitude of the forward acceleration varied according to the above-stated study design, whereas the subsequent backward acceleration was determined by the 2.4 s and the difference in the belt velocity at the two end of this duration.

The novel overground slip was induced on a pair of low-friction movable platforms embedded side-by-side in the walkway (Fig. 2b). Each movable platform was mounted on top of two force plates (AMTI, Newton, MA), allowing real-time ground reaction force (GRF) to be measured during each trial (Yang et al., 2007). The movable platforms were firmly locked during walking trials and unlocked in the slip trial by a computer controlled release mechanism at the instant of subjects' right heel strike on the right platform. Again, the subjects were never told about the location, timing and how a slip would occur. The subjects wore a safety harness during the whole experiment, which was connected through a load cell (Transcell Technology Inc., Buffalo Grove, IL) to the treadmill protective arch (Fig. 2a) or a trolley-and-beam system mounted on the ceiling above the walkway (Fig. 2b). The overhead trolley-and-beam system only exerted minimal amount of the pull (3.5 ± 1.2 N) through the harness on the subjects during the regular walking trials across the walkway. Kinematics of full-body marker set (26 body markers and 4 ground markers) was recorded by an eight-camera motion capture system (Motion Analysis Corporation, Santa Rosa, CA) at 120 Hz synchronized with the force plates and load cell at 600 Hz. A backward loss of balance (BLOB) was registered when trailing foot landed posterior to the slipping leading foot. A fall was detected when the peak force recorded by the load cell in the harness system exceeded 30% of body weight (Yang and Pai, 2011).

2.4. Outcome variables

The performance on the novel overground slip for the four treadmill training groups and the CTRL group was analyzed to examine for the generalization of training effect. The COM state stability was computed based on the theory of dynamic feasible stability region (Pai and Patton, 1997). The body COM kinematics was calculated using a 13-segment rigid body model with gender-dependent segmental inertial parameters (de Leva, 1996). The dynamic stability measurement reflects the simultaneous control of both COM position and velocity relative to BOS. The relative position and velocity of COM/BOS were referenced to the rear edge of BOS (the right heel) and normalized by foot length (l_{BOS}) and $\sqrt{g \times bh}$, respectively, where g is the gravitational acceleration and bh represents the body height. The COM stability was calculated as the shortest distance from the COM motion state to the dynamic feasible stability boundary against BLOB under slip conditions (Fig. 5). Stability with negative value means the stability of COM state was slower and/or more posterior than the boundary. Higher stability values indicate greater stability against BLOB (Pai et al., 2003). The key outcome measures included proactive and reactive control of stability. Proactive control of stability was characterized by the instantaneous stability value at right touchdown (RTD), which generally occurs 30 ± 20 ms before the slip onset (Pai et al., 2014), and reactive control of stability was characterized by the instantaneous stability value at the subsequent left liftoff (LLO), which generally occurs 150 ± 30 ms after the slip onset (Yang et al., 2013). Timing of RTD and LLO was identified from the vertical GRF together with motion analysis. Several variables including relative COM/BOS position, relative COM/BOS velocity, recovery step length, reactive BOS velocity were calculated to further understand the contributing factors to adaptive changes in the reactive control of stability. The recovery step length was calculated by the distance of the left-to-right heel at the touch down of the left foot and normalized to the body height (bh). The BOS (slip) velocity was calculated as the velocity of the right movable platform.

2.5. Statistical analysis

To test the first and second hypotheses, the data of stability from the four training groups were pooled in one group (n=36) and compared with the CTRL group (n=9) for changes in proactive and reactive control (Fig. 3). A two way ANOVA was used to determine whether there was an interaction effect between the two events (proactive vs. reactive) and the two groups (training vs. control) on stability. To test the 3rd and 4th hypothesis, a one way ANOVA was performed between the five groups (HI, LO, INCR, DECR, CTRL). Significant main effects with follow-up linear contrasts and planned comparisons (t-tests) were illustrated on the following variables: proactive stability, reactive stability, reactive COM/BOS

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