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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 improved 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), and progressively-increasing intensity (INCR with a block-to-block acceleration varied from 6 to 12 m/s^2) 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 advantage over the progressively-decrease or the low training strategy. (243 words)

Keywords

perturbation; motor learning; generalization; stability; proactive; reactive

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Conflict of interest statement

None.

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 et al., 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 overgournd 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 el 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 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-meter 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).

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 second speed up, followed by a 5.5 second steady state with a backward-moving belt speed of 1.2m/s. After eight to sixteen 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 3nd 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 position, reactive COM/BOS velocity, recovery step length and reactive BOS velocity among the five groups (Figs. 4 and 6). All statistics were analyzed using SPSS 22. The p values below 0.05 were considered statistically significant.

3. Results

Upon the novel overground slip, two subjects in CTRL group fell (22.2%); one subject fell in LO group (11.1%); while no one fell in HI, INCR and DECR groups (0%), one subject in HI even successfully walked over without BLOB. The pooled treadmill training group (n=36) showed significantly increased stability compared with the CTRL group (n=9) in both proactive and reactive control [main effect: $F(1, 86) = 24.169$, $p < 0.001$, Fig. 3]. And there was significant interaction between event (proactive vs reactive) and group (training vs control) [main effect: $F(1, 86) = 4.898$, $p = 0.03$, Fig. 3] with a significantly greater change in reactive control of stability between the control and the training groups than seen in proactive control of stability.

The magnitude of the group means in proactive and reactive control of stability displayed a clear ascending order from CTRL, LO, DECR, INCR, to HI, which is the same for both [main effect in proactive control: $F(4, 40) = 4.881$, $p = 0.003$; linear trend: $F = 19.102$, $p < 0.001$; main effect in reactive control: $F(4, 40) = 6.291$, $p = 0.001$; linear trend: $F = 23.764$, $p < 0.001$, Figs. 4 and 5]. Planned comparison revealed that HI, INCR and DECR groups were significantly better than CTRL (HI vs. CTRL, $p < 0.001$, INCR vs. CTRL, $p = 0.002$, DECR vs. CTRL, $p = 0.025$, Fig. 4) for proactive control of stability, whereas HI, INCR and DECR also had better reactive control of stability than did CTRL (HI vs. CTRL, $p < 0.001$, INCR vs. CTRL, $p = 0.002$, DECR vs. CTRL, $p = 0.004$, Fig. 4). HI group showed significantly higher stability than LO group in both proactive ($p = 0.013$, Fig. 4) and reactive control ($p = 0.008$, Fig. 4). Although there was a trend displayed, there was no significant difference between INCR and DECR groups for both proactive and reactive control of stability ($p > 0.05$, Fig. 4).

The change in stability was accompanied with a reactive forward-shift in the relative COM/BOS position [main effect: $F(4, 40) = 3.841$, $p = 0.01$; linear trend: $F = 11.519$, $p = 0.002$; planned comparison: HI vs. CTRL, $p < 0.001$, DECR vs. CTRL, $p = 0.035$, HI vs. LO, $p = 0.048$, Fig. 6a], increase in the relative COM/BOS velocity [main effect: $F(4, 40) = 3.539$, $p = 0.015$; linear trend: $F = 13.089$, $p = 0.001$; planned comparison: HI vs. CTRL, $p = 0.004$, INCR vs. CTRL, $p = 0.004$, DECR vs. CTRL, $p = 0.026$, Fig. 6b], decrease in the recovery step length that landed posteriorly [main effect: $F(4, 40) = 4.376$, $p = 0.005$; linear trend: $F = 14.929$, $p < 0.001$; planned comparison: HI vs. CTRL, $p = 0.001$, HI vs. LO, $p = 0.001$, Fig. 6c] and decrease in the BOS (slip) velocity [main effect: $F(4, 40) = 3.146$, $p = 0.024$; linear trend: $F = 10.923$, $p = 0.002$; planned comparison: HI vs. CTRL, $p = 0.001$, INCR vs. CTRL, $p = 0.015$, Fig. 6d].

4. Discussion

The results of the present study supported the first hypothesis that overall, treadmill-slip training improved the control of stability on a novel overground slip, and it further supported the second hypothesis that the improvement in reactive control of stability was more prominent than that in proactive control of stability. The data also supported our 3rd hypothesis, demonstrating that high intensity (HI) had a greater effect than low intensity (LO) on the generalization of stability control from treadmill training to overground walking. The results did not fully support the 4th hypothesis because there was no significant difference detected between the progressively-increasing training intensity (INCR) and the progressively-decreasing training intensity (DECR).

While the treadmill training did yield improvement of proactive control of stability (27.1%) in comparison to that of the CTRL, such improvement was greater in reactive control of stability (44.3%, Fig. 3). The improvements in reactive control of stability after treadmill training was characterized by a more forwardly-shifted relative COM/BOS position (which was in part due to a shortened length in recovery step that landed posteriorly), and a faster relative COM/BOS velocity (which was primarily due to a slower forward slip velocity, Fig. 6). While proactive control of stability represents a first line of defense against falling, reactive control of stability is the only other line of defense to prevent a fall (Pai et al., 2003). Previous studies examining mechanisms of adaptation to overground slips have demonstrated that a feedforward change in proactive stability resulting from change in step length and in foot and knee angle at touchdown can influence the reactive stability by altering the braking impulse and hence reducing the slip intensity (its displacement and velocity) (Bhatt et al., 2006b). Comparing the before and the after trials of the regular walking, treadmill training brought significant improvements in proactive control of stability, characterized by more forwardly positioned COM that led to greater COM stability in the post-treadmill training baseline trials. This is consistent with the previously reported results (Fig 4, in Yang et al., 2013)."

The similarity in context between training trials and subsequent assessment trials is known to affect the amount of generalization (Bhatt and Pai, 2009). Repeated overground-slip training has shown to yield greater amount of reactive stability improvement in post-training than did the same number of repeated treadmill-slips (Yang el al. 2013). Compared to the control group without training, the reactive stability improved by 157% after repeated overground-slip training, while it improved by 59.7% after the same number of repeated treadmill-slip training (Yang el al. 2013). Similarly, the high intensity group (HI) in the present study improved 63.8% in the reactive control of stability than the control. Hence, the generalization obtained from indirect treadmill-slip training to resist falls during overground walking was less than that of the improvement obtained from direct overground-slip training.

The investigations on various training strategies included in the present study shed new light on our understanding of motor control and learning. The result that high intensity training (HI) group yielded better generalization than low intensity training (LO) group was consistent with previous studies, which demonstrated that high training intensity induce greater motor learning than low training intensity. For example, it has been demonstrated that older adults who undertook higher intensity exercise training could have better stabilization of standing posture following perturbation from a movable platform (Brauer et al., 2008). Moreover, large motor errors, presumably associated with higher training intensity, are considered to induce better learning because motor cortex excitability modulates with walking difficulty rather than adaptation (Jayaram et al., 2011). Larger errors from repeatedly practice on the split-belt treadmill training were also associated with a faster rate of re-learning the next day among young adults (Malone et al. 2011). Further, a reduction in the gastrocnemius response was found over trials of rotational perturbations in low intensity (Hansen et al., 1988), which could be attributed to habituation of the initial response, supporting that low intensity training may not yield significant training effects.

It is postulated that the progressively-increasing intensity might result in a better generalization than progressively-decreasing intensity, because the former is more consistent with natural progression of motor learning more than the latter. People are more likely to learn from easiest level before gradually progress to the difficult levels. Though there is little direct evidence in the literature to support this notion, fear conditioning studies have examined the effect of gradual extinction of threatening perturbation compared with gradual reinforcement of it (Gershman et al., 2013). The study revealed that gradual extinction (decrease) of a perturbation better inhibit the motor memory than gradual reinforcement (increase) did. If this can draw a parallelism here, the results suggest that the approach inducing a gradual decrease in intensity during motor learning might inhibit memory and hence a weaker impact than a gradual increase approach. In spontaneous overground-slip training the slip intensity (speed and acceleration) were the highest on the very first slip and it reduced as adaptation was taking place (Bhatt el al., 2006a). This observation will argue for the DECR strategy when comes to slip perturbation training (Yang el al., 2013). In spite of these controversies, our results revealed that the advantage the INCR had was only marginal in comparison to the DECR strategy.

There are several limitations in the present study. This study was designed to compare immediate generalization of different treadmill-slip training strategies to overground slip perturbation on healthy young adults. The small sample size may attribute to only a significant linear trend rather than a consistent corresponding post-hoc between group differences. The present study did not explore how different populations would respond to the different training strategies. Though the high intensity treadmill-slip training (HI) appears to be the most effective way for young adults to get the best generalization, this paradigm might be difficult to implement among the older adults or individuals with movement disorders. Hence for the frail individuals, the progressively-increasing intensity training (INCR) might be a reasonable alternative to reduce training difficulties and to build up confidence.

In summary, the present study represents the first attempt to investigate how to maximize treadmill-slip training effect with different treadmill-slip training strategies. The treadmill training could improve the control of stability in overground walking, and the improvement in reactive control of stability was more prominent than that in proactive control. While higher training intensity can lead to better generalization as postulated, a progressively-increase in intensity did exhibit some advantage over the progressively-decrease or the low intensity training strategy.

Acknowledgments

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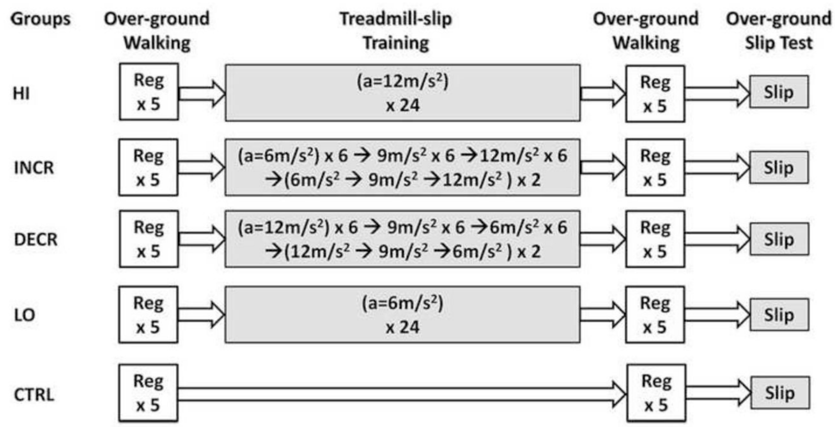

Fig. 1.

Study design to compare the generalization of different treadmill-slip training paradigms to a novel overground slip. In the treadmill training groups, every subject first performed five regular walking trials as baseline trials. After that, subjects in each treadmill group experienced different training paradigms. Subjects in the HI and the LO group had 24 continuous slips with acceleration at 12 m/s2 and 6 m/s2, 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/s2 for INCR and 12, 9 to 6 m/s2 for DECR). For the last two mixed blocks of three trials each, the acceleration within each block increased from 6 to 12 m/s2 (INCR) or decreased from 12 to 6 m/s2 (DECR). After the treadmill training, subjects went back to the same walkway for five trials before experiencing a novel overground slip. This slip served to test generalization of the training effects. Subjects in the CTRL group only experienced a novel overground slip after ten walking trials.

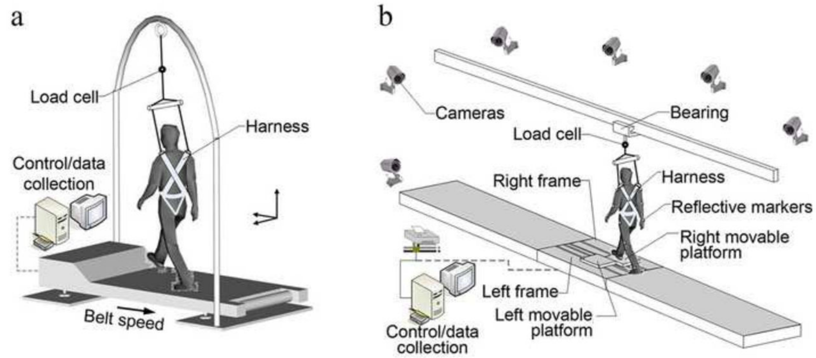

Fig. 2.

(a) The computer-controlled treadmill for slip perturbation training, (b) the overground walkway and the imbedded movable platforms. The treadmill-slip was induced by a sudden reduction on the backward speed of the treadmill top belt. The overground slip was triggered by the release of two side-by-side low-friction moveable platforms.

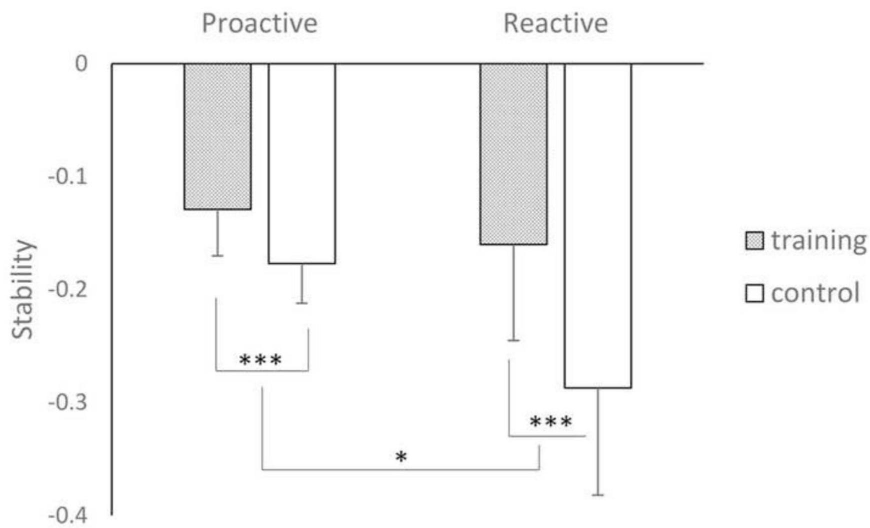

Fig. 3.
The proactive and reactive COM stability of the pooled training group (n=36) comparing with the control group (n=9) upon a novel overground slip. The training group data was pooled from the four training groups. *: $p<0.05$; ***: $p<0.001$.

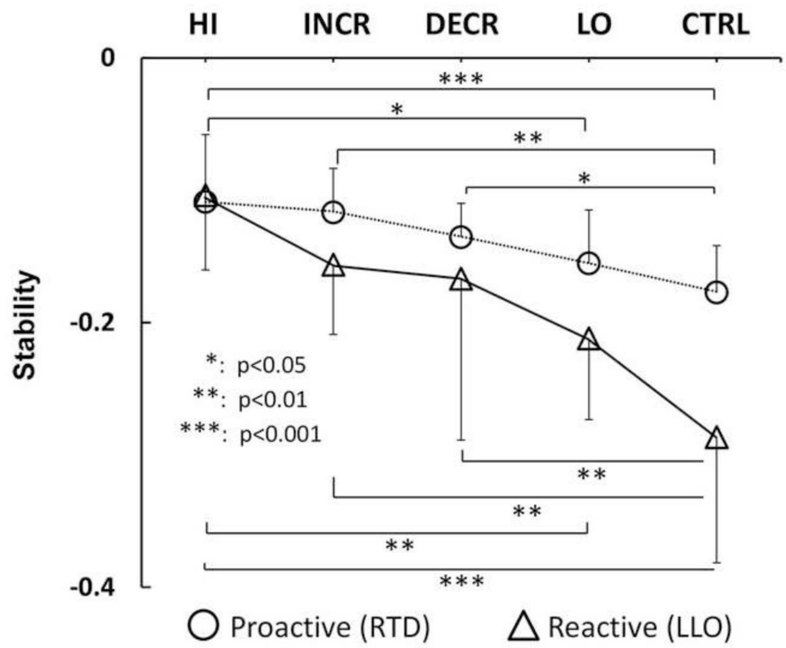

Fig. 4.

The proactive and reactive COM stability of the five groups upon a novel overground slip. The measurement of proactive COM stability was taken at right foot touchdown. The measurement of reactive COM stability was taken at left foot liftoff. The straight lines collecting the data points indicated that significant linear trends existed among group means.

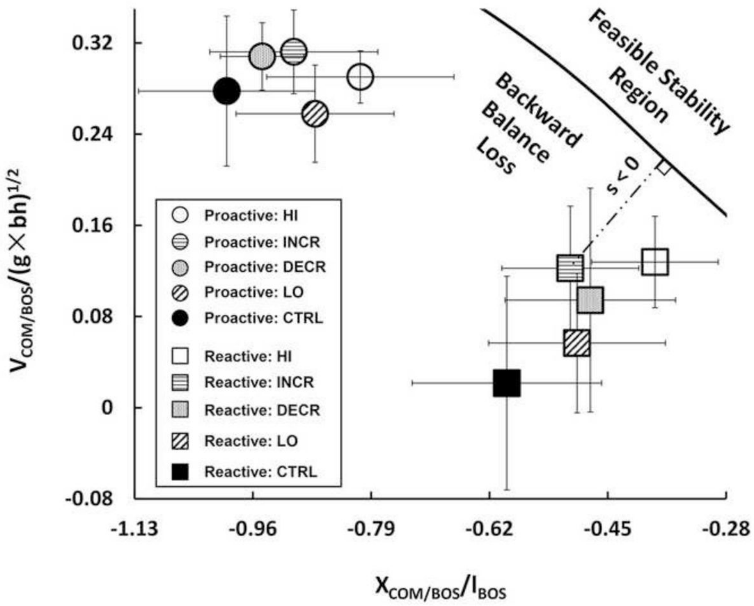

Fig. 5.

The instantaneous COM state of the five groups in proactive control (right touch down) and reactive control (left lift off) upon a novel overground slip (Y axis: relative COM/BOS velocity; X axis: relative COM/BOS position). S indicates the stability of a COM state, which is the perpendicular distance (dash line) between the COM state and the threshold for backward balance loss (thick solid line between backward balance loss and feasible stability region). S<0 means the stability of COM state was slower and more posterior than the boundary. Greater stability values indicate greater stability against backward balance loss (Pai et al., 2003). Position and velocity of the COM relative to the BOS are dimensionless variables expressed 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 the body height.

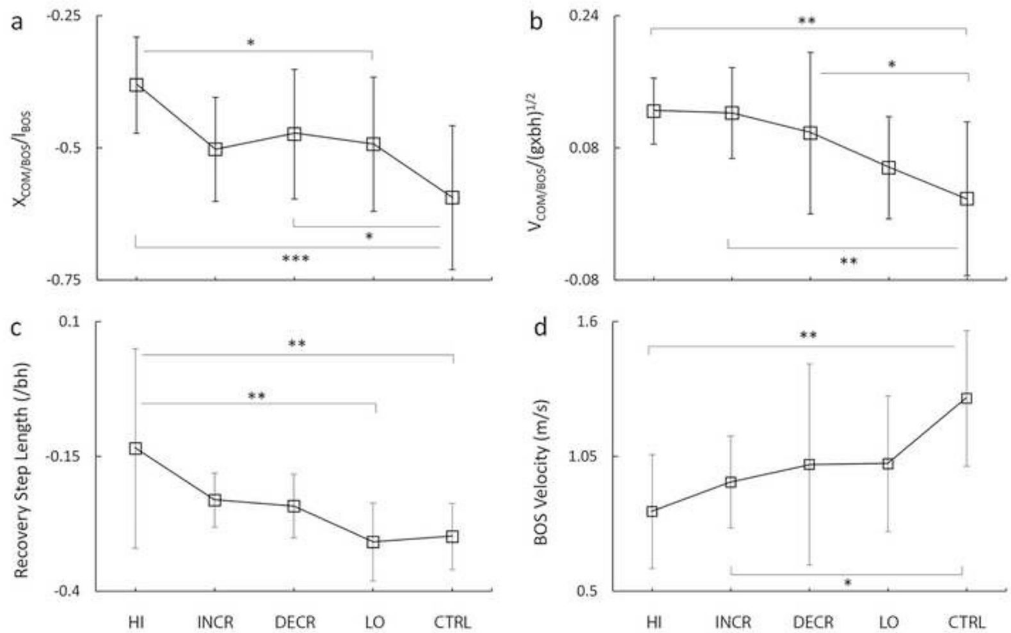

Fig. 6.

Comparison of the (a) reactive relative COM/BOS position, (b) reactive relative COM/BOS velocity, (c) recovery step length, and (d) reactive BOS (slip) velocity upon a novel overground slip among the five groups. *: $p<0.05$; **: $p<0.01$

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