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Generalization of treadmill perturbation to overground slip during gait: Effect of different perturbation distances on slip recovery

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Abstract

Treadmill-perturbation training (TM-training) may improve a person's fall-resistance, whereby adjusting slip distance can be a simple way to manipulate training intensity. The purpose of this study was to determine the effects of different slip distances in TM-training (12-cm vs. 18-cm) on its generalization to the recovery from a novel "free" slip during overground walking. Generalization here means the ability to apply learned skill from TM-training to slip recovery during overground walking. Thirty-six young adults in the TM_12 or the TM_18 group underwent either a 12-cm or an 18-cm slip during the treadmill walking for seven times, or in the control group were not exposed to any perturbation. Their responses were also contrasted with previously reported results from overground-perturbation training (OG-training) in which participants received either a 12-cm or an 18-cm slip during level walking with the same number of repetitions. Everyone was then exposed to the same generalization test during a novel "free" slip in overground walking. Their proactive and reactive control of stability was measured and compared. TM-training displayed a significant training effect in comparison to the control group ($p < 0.05$), while most of the improvements were found in the reactive control of stability and were much-limited in comparison to that of OG-training. Also unlike OG-training, no significant differences were found between the results obtained from the TM_12 and the TM_18 groups ($p > 0.05$). These results underscore the further needs to investigate the potential of the treadmill as a convenient instrument that can effectively deliver perturbation training.

Keywords

Generalization; Proactive; Reactive; Intensity; Stability; Falls

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Conflict of interest statement

None declared.

1. Introduction

Falls among older adults may cause injury-related hospitalization and accidental death. An estimated one-third of community-dwelling older adults over 65 years old fall annually and the rate is increasing to 40% in those over 80 years old (Tinetti et al., 1988). Fear of falling in itself can decrease mobility and activity (Stenhagen et al., 2014). As a result, the quality of life decreases (Stenhagen et al., 2014).

Slip-related falls are one of the predominate reasons of fractures (Luukinen et al., 2000). Perturbation training is an emerging paradigm to induce fall-resistance adaptation, which is a process of error-driven motor learning (Lockhart, 2008; Pai and Bhatt, 2007; Yang et al., 2013). This kind of learning has also shown a measurable generalization effect. For instance, repeated slips can reduce slip-induced backward loss of balance outside of the training contexts by improving the proactive (feed-forward) and the reactive (feedback) control of stability and limb support (Wang et al., 2011). The generalization can occur when we assume that the central nervous system recalibrates its internal representation of the center of mass (COM) stability limits. It is so general that it becomes the basis for guiding this person's feed-forward adjustments and feedback responses in different tasks and conditions (Bhatt and Pai, 2008; Wang et al., 2011; Bhatt and Pai, 2009). This generalization might have contributed to the reduction of older adults' annual risk of falls outside of the laboratory training context in everyday living (Pai et al., 2014).

The treadmill is a popular tool in rehabilitation because it is not only portable but also relatively safe to use, in part due to the capability to precisely adjust its intensity during the training. In a recent study, significant generalization of training effects was observed from treadmill-perturbation to a novel slip induced during overground walking (Yang et al., 2013). If the treadmill-perturbation training effect on the control of stability can be modulated and generalized to real-life overground slips, then such a device can bring new applications to physical rehabilitation. In this connection, slip distance may be used as means to modify the intensity, just as in overground-perturbation training (Yang et al., 2014). While both 12-cm and 18-cm slip training could improve proactive and reactive control of COM stability (to a different degree) during a novel "free" (unconstrained) slip in overground walking (Yang et al., 2014), it is unclear that similar effects can be reproduced with treadmill-perturbation training. The ability to reduce treadmill-perturbation training intensity could be essential for frail older adults who may have limited tolerance for such perturbation training.

The purpose of the present study was to determine the effect of different slip distances (i.e., 12-cm vs. 18-cm) of treadmill-perturbation training (TM-training) on generalization during the recovery from a novel "free" slip induced during overground walking. Generalization here means the subjects' ability to apply what they have learned from treadmill-slip training to slip recovery during overground walking. We expected that similar to the overground-perturbation training (OG-training) (Yang et al., 2014), TM-training could also improve the control of stability (Hypothesis One), both proactive and reactive; whereby a longer slip distance (18-cm vs. 12-cm) in TM-training would induce a more robust generalization (i.e. better stability) when responding to a novel "free" slip during overground walking

(Hypothesis Two). Nevertheless, OG-training might yield a better generalization effect due to a higher degree of context similarity between OG-training and OG generalization test (Hypothesis Three).

2. Methods

2.1. Study design

Thirty-six healthy young adults (age= 26.74 ± 4.9 , female=18) participated in the present study. They were evenly assigned to three groups: two treadmill-perturbation training groups with either 12-cm perturbation distance (TM_12) or 18-cm perturbation distance (TM_18), and a control group which received no treadmill-perturbation training. It is a sample of convenience, though post-hoc analysis revealed no between-group difference during their baseline walking. In addition, data for other two groups from a previously published study were included in the analysis (Yang et al., 2014). Those two groups (similarly each with 12 healthy young subjects) received repeated constrained-slips either with a 12-cm slip distance (OG_12) or with an 18-cm slip distance (OG_18) during overground walking. All subjects provided written informed consent, and this study was approved by the institutional review board at the University of Illinois at Chicago.

2.2. Experimental setup

The Active Step treadmill (Simbex, Lebanon, NH) was applied in order to induce perturbation to simulate slips in walking (Fig. 1a). Each slip trial profile consisted of 1.5 s ramping-up duration followed by four to 10 steps of steady state walking on a backward-moving belt at a speed of 1.2 m/s. Subjects did not know when the perturbation would occur before the belt suddenly accelerated for 0.2 s in the forward direction at 6 m/s^2 for the TM_12 and 9 m/s^2 for the TM_18. The characteristics of treadmill perturbation were to cause forward displacement of subjects' base of support (BOS) relative to their center of mass (COM) (Fig. 1c and d).

The generalization test was conducted on an overground walkway. A sliding device was embedded in the middle section of a 7-m walkway to induce slips during overground walking (Fig. 1b). This device consisted of a pair (i.e., right and left) of low-friction, passively movable platforms. Each platform was mounted to an aluminum track via ball bearings and placed on top of a pair of tandem force plates bolted to the ground (AMTI, Newton, MA) for recording ground reaction forces (Yang et al., 2007). Both platforms were firmly locked in place, but could be unlocked by a computer controlled release mechanism at the instance of participants' right heel strike on the right platform, without alerting the subjects. Once released, the right platform could slide up to the entire length of the track (150 cm). All subjects were able to exert reactive control to terminate their slip within a 45–90 cm range ($78.1 \pm 33.3 \text{ cm}$) (Yang et al., 2009). Therefore, 150 cm is sufficient to afford them a “free” (unconstrained) movement of slip without any artificial interruption in which this slipping platform would hit a stopper before it spontaneously stopped sliding.

Previous study used an identical walkway setup (Yang et al., 2014). The slip distance of 150 cm was manually reduced during the training, by adjusting the locking system with the mechanical stopper. This mechanism allowed the previous study to use the same 12-cm or

18-cm slip distance for training, except it only occurred during the overground walking (Fig. 2c and d) (Yang et al., 2014). The generalization test was also identical in both studies and therefore, the results of these two studies were comparable from this perspective.

All subjects wore their running shoes and were connected to a full-body safety harness attached to a load cell by a pair of shock absorbing ropes, which were attached to a low friction ceiling mounted track, to protect them from injuries. The loadcell signal was recorded and later applied to detect a fall from recovery, when its value, integrated over time, exceeded 30% of the subject's body weight (Yang et al., 2007).

2.3. Protocol

Every session for all groups started with eight overground walking trials at each person's preferred speed and manner that served as a baseline measurement (Fig. 2a and b). The TM-training (and the OG-training in the previous study in Fig. 2c and d) groups would then begin their training, which consisted of the same amount of perturbations as did the OG-training groups. It always began with a block of five perturbations, followed by a block of five non-perturbation trials, and then another block of two perturbations (Fig. 2a–d). The control group experienced the same block of eight baseline walking trials before encountering the same novel “free” slip trial (Fig. 2e).

2.4. Data collection

Thirty reflective markers were placed on the subjects' body and platforms, and joint kinematics were recorded using an 8-camera motion capture system (Motion Analysis Corporation, 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). Three-dimensional locations of joint centers, heels, and toes were computed from the filtered marker positions. Force plates, loadcell, and platform trigger-release onset signal were collected at 600 Hz and synchronized with motion data at the time of data collection.

2.5. Outcome measure

The COM (center of mass) state stability in the present study was computed based on the theory of dynamic feasible stability region (Pai and Patton, 1997). The COM motion state composed of two factors, the COM position and velocity, which were each quantified to examine the contribution of each factor to any changes in stability following training. The body COM kinematics were calculated using a 13-segment rigid body model with gender-dependent segmental inertial parameters (de Leva, 1996). The COM position and velocity were calculated relative to the rear of base of support (BOS) (i.e. the right heel) and normalized to become a dimensionless unit by foot length (l_{BOS}) and $\sqrt{g \times bh}$ respectively, where g is the gravitational acceleration, and bh is body height. The COM stability was calculated by the shortest distance from the dynamic feasible stability region in COM motion state (Yang et al., 2007), which is therefore also a dimensionless measure. Higher stability values indicate greater stability against backward balance loss (Pai et al., 2003). Stability was assessed at two points in time to assess proactive and reactive contributions. Proactive control of stability was obtained at the instant before slip (i.e., instant of right

touch down or RTD), and reactive control of stability was obtained after slip (i.e., instant of left lift off or LLO). Several variables including slip distance from RTD to LLO, and slip (BOS) (i.e., right heel marker) velocity at LLO were calculated to further understand what had contributed to the adaptive changes in the reactive control of stability.

2.6. Statistical analysis

Data of five groups, the TM_12, the TM_18, the OG_12, the OG_18, and the control groups, were analyzed using one-way ANOVA. Based on the statistical results from the one-way ANOVA, priori planned *t*-tests were conducted to compare differences between groups, TM_12 and TM_18 vs. control (hypothesis One), TM_12 vs. TM_18 (hypothesis Two), and TM_18 vs. OG_18 (hypothesis Three). All analysis was performed with SPSS 22 (IBM, Chicago, IL). The *p*-values below 0.05 were considered statistically significant.

3. Results

No one fell in the TM_18 and the OG_18 groups. One subject in each of the TM_12 and OG_12 groups and three subjects in the control group fell during the generalization test.

3.1. Proactive control

The proactive control of stability improved only marginally following treadmill-perturbation training [main effect: $F(4, 55)=5.231, p<0.05$]. While TM_18 group had significantly better proactive control than the control group ($p<0.05$), the TM_12 did not ($p>0.05$, Fig. 3). There was no significant difference between TM_12 and TM_18 ($p>0.05$). Additionally, there was no significant difference between TM-training and OG-training ($p>0.05$, Fig. 3). Any changes in proactive control of stability could only be attributed to an anterior shift in the COM position [main effect: $F(4, 55)=2.535, p=0.05$], while the COM velocity remained unchanged during overground walking [main effect $F(4, 55)=1.648, p>0.05$, Fig. 3c].

3.2. Reactive control

The reactive control of stability improved significantly following the training [main effect: $F(4, 55)=39.840, p<0.05$]. Planned comparisons indicated that TM_12 and TM_18 both had significantly greater reactive stability than the control group (both $p<0.05$). Still there was no significant difference between TM_12 and TM_18 in the reactive control ($p>0.05$), unlike the OG-training. Further, TM_18 did not have greater improvement in stability than OG_18 ($p<0.05$, Fig. 4a).

The improvement in the reactive control of stability was achieved by change in the COM position [main effect: $F(4, 55)=11.707, p<0.05$] and in COM velocity [main effect: $F(4, 55)=17.559, p<0.05$]. TM_18 was in a significantly higher and anterior position and greater COM velocity than the control group ($p<0.05$, Fig. 4b and c). Yet again, there was no significant difference between TM_12 and TM_18 ($p<0.05$), unlike its OG-training counterpart. And again, the anterior shift in COM or the increase in the COM velocity of the TM_18 was not as great as in the OG_18 ($p<0.05$, Fig. 4b and c).

These changes in the relative COM position and velocity were primarily attributable to the corresponding changes in the control of the slip distance (i.e., making it shorter) and BOS

velocity (i.e., making it slower) in the generalization test [main effect for distance: $F(4, 55)=4.476, p<0.05$; and main effect for velocity: $F(4, 55)=20.715, p<0.05$]. In slip distance, however, there was no significant difference between the TM-training and the control groups ($p>0.05$). There was no significant difference between TM_12 and TM_18 ($p>0.05$), unlike its OG-training counterpart. TM_18 slip distance was significantly longer than that of OG_18 ($p<0.05$, Fig. 5a). While TM-training was able to significantly slow down slip velocity in comparison to the control group ($p<0.05$), the difference between TM_12 and TM_18 was not significant ($p>0.05$). And again, the TM_18 did not improve as much as the OG_18 ($p<0.05$, Fig. 5b).

4. Discussion

TM-training did improve the control of stability upon the generalization test; most prominently it improved the reactive control of stability following the novel “free” slip in over ground walking. Surprisingly, however, two slip distances in TM-training apparently did not yield sufficient differences in training intensity to alter the results of the generalization test as their counterparts in OG-training did. As a result, such generalization was also much limited in comparison to that achieved through OG-training.

The treadmill-perturbation training in the present study clearly improved stability by providing the experience of trial-and-error with repeated slips, and such adaptation in the CNS may very well be attributable to the habituation accompanying the reduction of error in response to slips. Nonetheless, the concepts of habituation and generalization may differ. Habituation refers most often to a reflex based motor learning, resulting from a direct connection between the stimulus and the response. Generalization takes place when the (acquired) adaptation persists in (or transfers to) the contexts outside of the original training or the acquisition conditions, such as from the TM-training to the overground generalization test in the present study. The same internal representation of the stability limits updated during TM-training and then applied during the generalization test of the Hypothesis One, could well account for the results of the improved control of stability we observed in the present study (Wang et al., 2011).

In general, intensity is one of the key factors affecting motor learning; whereby high training intensity induces greater changes that directly correlate with improved behavioral outcomes (Horak et al., 1989). For example, high intensity training on a treadmill (e.g., higher belt speed) with body weight support yields higher self-selected speed during overground walking by 40% (Sullivan et al., 2002; Fisher and Sullivan, 2001). The TM-training intensity was higher in the previous study that employed a similar generalization test (Yang et al., 2013). It had a greater number of repetitions (15 or more) and a higher maximum slip distance and acceleration (24 cm and 12 m/s^2). Consequently, it yielded significantly better proactive ($-0.11 \pm 0.05, p<0.05$) and reactive ($-0.12 \pm 0.09, p<0.05$) control of stability than the outcomes in the present study. Another TM-training study employed 6 m/s^2 and 12 m/s^2 (Liu et al., in press), where a higher intensity did yield greater proactive and reactive control of stability during the same generalization test. The difference from 12 cm to 18 cm resulting from a change in acceleration from 6 m/s^2 to 9 m/s^2 in the present study was

apparently insufficient to yield any meaningful difference for the generalization, and thus failed to support our Hypothesis Two.

The present study design also differed substantially from the previous TM-training study (Yang et al., 2013), which used a “success-or-failure strategy” to down modulate the intensity of the next perturbation. In contrast, the intensity of the present study was predetermined and remained constant for each group. Rather than to search for the lowest intensity level where a *successful* recovery (i.e. without losing balance) was guaranteed in three out of five consecutive trials (Yang et al., 2013), the intensity of the present study was predetermined. Specifically, TM-training here was confined by the same slip distances as those applied in a previous study of OG-training (Yang et al., 2014). Such design enabled us to directly compare the results of TM-training with those of the OG-training in order to test Hypothesis Three.

The differences between the two outcomes were quite striking, and they can be accounted for in part by the similarities and differences between the training and the test conditions. For the OG-training and the ensuing test trial, all slips occurred consistently under the right side. For TM-training, the device employed in this study could not precisely control the timing of the slip onset with respect to the leading foot on the ground (left or right), and hence subjects received slips under both sides. Post-hoc analysis indicated that 50% of perturbations occurred under the left side. To be specific, only 6 out of combined 24 subjects experienced 5 perturbations or more on the right side during the treadmill training, which would substantially reduce the actual training intensity. Additional post-hoc analysis also revealed that the onset timing of TM-perturbation occurred at $33 \pm 12\%$ of the gait cycle, which was measured from the slipping foot touchdown to its next touch. In contrast, the slip onset occurred at $5 \pm 4\%$ of the gait cycle in OG slip. The lack of precise control of the slip onset and its timing in the gait cycle with this specific device is likely to have contributed to the ensuing differences between the training and the generalization test and the inferior training effect.

The substantial amount of generalization noted in the OG-training may also be attributable to the similarity in context between training trials (12-cm or 18-cm OG slips) and the generalization test and thus lent support to our Hypothesis Three. Prior to the onset of the “free” slip, both of these two groups had made significant proactive adjustments, which could affect the subsequent reactive control of stability by reducing the BOS perturbation intensity to reduce risk of falls. Such adjustments included reducing the foot angle for a more flat-footed landing (Yang et al., 2014), which is known to reduce the braking impulse by altering the biomechanics of both the leading and the trailing limbs and hence reducing the slip velocity (Bhatt et al., 2006). During the OG-training, the individual control of the ground reaction force beneath each foot also allows a person to actively modulate the slip velocity (to slow down and hence reduce slip distance). In contrast, for treadmill training, subjects were not afforded the learning opportunity to change the relative relationship between the leading and the trailing limbs. The treadmill belt speed cannot be actively controlled by the person. As result of that, the adaptive changes occurring in the TM-training groups were primarily attributive to the reactive control, which include the alteration in trunk angle and the improvement in the compensatory stepping response.

The present study has several limitations. The small sample size of the present study may limit its broad application. Based on the variability noted in the present study, a power analysis revealed that 102 subjects would be required to achieve an effect size=0.40 (large) at an alpha level of 0.05 and power of 0.95 to detect the generalization under the current conditions. Additionally, the inclusion of only healthy young adults cannot guarantee the findings to be applicable in an older population who has a greater tendency to fall. Further, the present study employed a commercially available, computer-controlled, motorized treadmill. Because the device was not specifically designed for the present study, the control of slip onset timing in a cycle or the side of perturbation (left or right) could not be precisely timed to closely mimic overground walking. Both of these discrepancies can possibly reduce the generalization.

In conclusion, TM-training can still improve stability control. Yet, controlling the same parameter may mean different things in TM- vs. OG-training. The latter would produce significantly greater generalization than the former during the test that is conducted during a “free” slip in overground walking.

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Fig. 1.

Schematics of the treadmill, which was used to produce slip-like perturbation (a), and the overground walkway and the movable platforms, which were used to the overground-perturbation training and a novel slip test (i.e., generalization test) (b). The profile of a treadmill trial with a perturbation distance of 12-cm and an acceleration of 6 m/s² (c) and the profile of a treadmill trial with a perturbation distance of 18-cm and an acceleration of 9 m/s² (d). Each perturbation trial profile consisted of 1.5 s ramping-up duration (from A to B) followed by four to 10 steps of steady state walking on a backward-moving belt at a speed of 1.2 m/s (from B to C). And then the belt quickly accelerated to -1.2 m/s in 0.2 s (from C to D). After the instant of perturbation (i.e., 0.2 s), the belt speed returned to 1.2 m/s (from D to E) and stopped after the ramp-down period (from F to G).

Fig. 2.

Schematics of the study designed to test the generalization of the treadmill-perturbation training and the overground-perturbation training on a novel "free" slip (i.e., generalization test) during the overground walking. All training groups received eight trials of the regular walking on the overground walkway before training. TM₁₂ (a), TM₁₈ (b), OG₁₂ (c), OG₁₈ (d) began with a block of five perturbations (slips), followed by a block of five non-perturbation trials, and then another block of two slip trials. The control group (e) started with eight trials of the regular walking without any training. After their training, all subjects received a novel slip (i.e., generalization test) at free slip distance (i.e., 150 cm) on overground.

Fig. 3.

Proactive control (i.e., prior to the novel slip onset): comparisons of groups' mean $\pm$ SD of the stability at right (i.e., slipping foot) touch down (RTD) (a), the center of mass (COM) position at RTD (b), and the COM velocity at RTD (c) between the treadmill-perturbation training groups (i.e., TM_12 and TM_18, $n=12$ for each), the overground-perturbation training groups (OG_12 and OG_18, $n=12$ for each), and the control group ($n=12$) on their 150-cm novel slip test (i.e., generalization test). Both the COM position and the COM velocity were relative to the rear edge of the base of support (BOS) and respectively normalized by foot length (l_{BOS}) and $\sqrt{g \times bh}$ (i.e., g represents the gravitational acceleration and bh represents the body height). Measurements were recorded at the pre-slip instant (i.e., right foot touchdown [RTD]) during a novel slip trial (i.e., generalization test), * $p<0.05$, ** $p<0.01$, *** $p<0.001$.

Fig. 4.

Reactive control (i.e., following the slip onset): comparisons of groups' mean $\pm$ SD of the stability at recovery foot lift off (LLO) (a), the center of mass (COM) position at LLO (b), and the COM velocity at LLO (c) between the treadmill-perturbation training groups (i.e., TM_12 and TM_18, $n=12$ for each), the overground-perturbation training groups (OG_12 and OG_18, $n=12$ for each), and the control group ($n=12$) upon their 150-cm novel slip test (i.e., generalization test). Both the COM position and COM velocity were relative to the rear edge of the base of support (BOS) and respectively normalized by foot length (l_{BOS}) and $\sqrt{g \times bh}$ (i.e., the g represents the gravitational acceleration and the bh represents the body height). These measurements were recorded at the postslip instant (i.e., left lift off [LLO]) during a novel slip trial (i.e., generalization test), * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Fig. 5.

Comparisons of groups' mean $\pm$ SD of the slip distance at LLO (a) and the BOS (right heel) velocity at LLO (b) between the treadmill-perturbation training group (i.e., TM_12 and TM_18, $n=12$ for each), the overground-perturbation training group (OG_12 and OG_18, $n=12$ for each), and the control group ($n=12$) upon their 150 cm novel slip test (i.e., generalization test), * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.