Retention of improvement in gait stability over 14 weeks due to trip-perturbation training is dependent on perturbation dose

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Abstract

Perturbation training is an emerging approach to reduce fall risk in the elderly. This study examined potential differences in retention of improvements in reactive gait stability over 14 weeks resulting from unexpected trip-like gait perturbations. Twenty-four healthy middle-aged adults (41-62 years) were assigned randomly to either a single perturbation group (SINGLE, *n* = 9) or a group subjected to eight trip-like gait perturbations (MULTIPLE, *n* = 15). While participants walked on a treadmill a custom-built brake-and-release system was used to unexpectedly apply resistance during swing phase to the lower right limb via an ankle strap. The anteroposterior margin of stability (MoS) was calculated as the difference between the anterior boundary of the base of support and the extrapolated centre of mass at foot touchdown for the perturbed step and the first recovery step during the first and second (MULTIPLE group only) perturbation trials for the initial walking session and retention-test walking 14 weeks later. Group MULTIPLE retained the improvements in reactive gait stability to the perturbations (increased MoS at touchdown for perturbed and first recovery steps; $p < 0.01$). However, in group SINGLE no differences in MoS were detected after 14 weeks compared to the initial walking session. These findings provide evidence for the requirement of a threshold trip-perturbation dose if adaptive changes in the human neuromotor system over several months, aimed at the improvement in fall-resisting skills, are to occur.

Introduction

Falls are a major cause of injuries and disability in the elderly population (Terroso et al., 2014). According to epidemiological studies increased fall risk becomes detectable by middle-age (i.e. about 50 years of age; Donaldson et al., 1990). Most falls in the elderly result from tripping during walking (Berg et al., 1997; Talbot et al., 2005), causing sudden loss of balance in the forward direction. To avoid falling, such unstable body dispositions require reactive postural adjustments in order to control the position and velocity of the centre of mass (CoM) relative to the base of support (BoS; Bhatt et al., 2006; Bierbaum et al., 2011; MacLellan and Patla, 2006). Improving such compensatory gait adjustments may be beneficial for fall prevention.

Perturbation training has emerged as a promising approach to reduce falls in the elderly (Gerards et al., 2017; McCrum et al., 2017) since several studies demonstrate significant improvements in reactive response in older adults after repeated exposure to various laboratory-induced mechanical gait perturbations (Bierbaum et al., 2011; Epro et al., 2018a; Lee et al., 2018; Pai et al., 2010). These improvements in reactive gait stability in the elderly can be retained over several months (Bhatt et al., 2012; Pai et al., 2014a) or even years (Epro et al., 2018b) without any additional training. This provides evidence that repeated externally induced gait perturbations may be an appropriate stimulus for the aged central nervous system to develop enhanced and retainable balance control strategies through refined neuromuscular coordination reducing fall risk (Pai et al., 2014b).

Previous studies showed that such reactive balance improvements can occur after merely a single perturbation exposure (Marigold and Patla, 2002; Pai et al., 2010). Though such a single trial effect seems promising, in particular for application with frail older adults, it has only rarely been investigated whether reactive gait stability improvements acquired through single perturbation exposure can be retained over a prolonged time-period (e.g. several months) in populations which are at higher fall risk. In contrast, retention of the robust effects obtained from multi-trial perturbation training sessions are already well established (Bhatt et al., 2012; Epro et al., 2018b; Pai et al., 2014a). However, to our knowledge only Liu et al. (2017) examined this topic, demonstrating that a single slip perturbation exposure can cause long-term retention effects.

In a previous study we were able to show retention in gait stability improvements over 14 weeks following a single bout of eight unexpected trip-like gait perturbations (Epro et al., 2018b). As a continuation, in this study we aimed to examine whether such retention effects may also be observed after single trip exposure i.e. whether the retention in gait stability improvements over 14 weeks is dependent on trip-perturbation dosage for a group of middle-aged.

Methods

Twenty-four healthy middle-aged adults (41-62 years; 12 of them men), with no known neurological or musculoskeletal impairments, took part in this study. The participants were randomly divided into two groups: (1) MULTIPLE, the reference group, (eight gait-perturbations initially and after 14 weeks; *n* = 15); and (2) SINGLE (a single gait perturbation initially and again after 14 weeks; *n* = 9). The two groups underwent equivalent periods of treadmill walking (20-25 min). The study was approved by the ethics committee of the German Sport University Cologne in accordance with the Declaration of Helsinki. All participants provided written informed consent after initial briefing.

About seven days prior to the initial measurement session all participants underwent treadmill familiarisation (h/p/cosmos pulsar 4.0; Nussdorf-Traunstein, Germany) consisting of ten minutes walking at $1.4\ m\ s^{-1}$. For perturbations, all participants again walked at a standardised velocity of $1.4\ m\ s^{-1}$ on a treadmill and received either one or eight unexpected gait perturbations using a custom-built brake-and-release system described previously (Epro et al., 2018ab; see supplementary material 1 for more detailed description). Note that our applied perturbation paradigm imposes *artificial* trips that may not fully replicate real-life trip situations (see supplementary material 2 for a typical recovery response to the perturbation). Therefore, in this manuscript the perturbation will be referred to as a "trip-like gait perturbation".

For electronic version: Insert supplementary material 2

In order to assess dynamic stability (specifically MoS) each participant was analysed before (Pre) and after 14 weeks (Post14w). Arrangements to assess dynamic stability control during treadmill walking have been described previously (Epro et al., 2018ab; McCrum et al., 2014; Süptitz et al., 2012, 2013). Briefly, a reduced kinematic model (Süptitz et al., 2013), consisting of five retro-reflective markers (radius 16 mm) placed at the seventh cervical vertebra and the greater trochanter and forefoot of the left and right legs, was tracked using a 10-camera motion capture system (120 Hz; Nexus 2.6.1; Vicon Motion Systems, Oxford, UK). The time-courses for the 3D coordinates of the markers were smoothed using a fourth-order digital Butterworth filter (cut-off frequency 20 Hz). The anteroposterior MoS was calculated at each foot touchdown (TD) for baseline gait, the perturbed step (Pert) and the first six recovery steps after perturbation (Reco1L-Reco6R) as the difference between the anterior boundary of the base of support (anteroposterior position of the toe projection to the ground) and the extrapolated centre of mass (Hof et al., 2005). TD was determined using two 2D accelerometers (1080 Hz; ADXL250; Analog Devices, Norwood, MA, USA) attached over the tibia of each leg (Süptitz et al., 2012). Our reduced kinematic model has been validated previously (Süptitz et al., 2013) as appropriately assessing MoS for unperturbed and perturbed walking and for wide ranging age groups, showing significant correlations with a full-body kinematic model (average across trials $r = 0.90$, $p < 0.01$).

Independent samples *t*-tests were used to assess potential differences in age, height and body mass between groups. A two-way repeated-measures ANOVA with factors group (MULTIPLE and SINGLE) and time point (first perturbation trial at baseline ($T1_{Pre}$) and after 14 weeks ($T1_{Post14w}$)) was conducted to determine retention of improvements in MoS during unexpected trip-like gait perturbation, separately for TD Pert and TD Reco1L. Note that only $T1_{Pre}$ and $T1_{Post14w}$ were considered for further analysis as the aim of this study was principally to examine retention effects following different perturbation training protocols rather than trial-to-trial adaptation within one session. The focus here was set solely on the first perturbation trials since trial-to-trial adaptation has been shown previously for healthy middle-aged adults (McCrum et al., 2014). Note that in order to check for acute effects in MoS after single trip exposure (without possibly affecting retention by adding another perturbation in group SINGLE) a two-way repeated-measures ANOVA with factor trial (first and second perturbation trial at initial training session, $T1_{Pre}$ and $T2_{Pre}$ respectively) and step (TD Pert and TD Reco1L) was conducted for group MULTIPLE. A further two-way repeated-measures ANOVA (factors: group, trial) was implemented for unperturbed gait (average of 12 consecutive steps of unperturbed walking with ankle strap attached, assessed prior to the first perturbation). In a case of significant main effect or interaction Bonferroni *post-hoc* correction was applied. The level of significance was set at $\alpha = 0.05$. All results in text and figures are presented as mean (SD). All statistical analyses were conducted using Statistica software (Release 10.0; Statsoft Inc, Tulsa, OK, USA).

Results

There were no significant differences in age (51.1 (6.0) years vs. 54.3 (4.0) years), body height (171.9 (12.0) vs. 180.1 (12.9) cm) and body mass (76.7 (14.0) vs. 79.3 (14.9) kg) between the two groups (MULTIPLE vs. SINGLE). One participant from group MULTIPLE was not able to cope with the task by grasping the treadmill handrails to prevent a fall after the novel trip-like gait perturbation ($T1_{Pre}$); hence only 23 participants were considered for analysis of dynamic stability. For baseline walking (12 consecutive steps), the two-way repeated-measures ANOVA revealed no statistically significant effects for MoS for time point ($T1_{Pre}$ and $T1_{Post14w}$) or group (MULTIPLE and SINGLE). Considering post 14 weeks, the analysis of MoS at TD Pert and TD Reco1L revealed a statistically significant time point x group interaction for both analysed steps ($F_{1,21} = 4.29$, $p = 0.05$ and $F_{1,21} = 9.66$, $p = 0.01$ for TD Pert and TD Reco1L respectively), indicating that the time effect on MoS was dose specific. Post-hoc tests revealed significantly higher MoS values ($0.001 < p < 0.01$) at TD Pert and Reco1L for $T1_{Post14w}$ compared to $T1_{Pre}$ for group MULTIPLE (see figure 1). In contrast, no statistically significant increases in MoS after 14 weeks were found for any of the analysed steps in group SINGLE (see figure 1). Regarding acute MoS changes, the two-way repeated-measures ANOVA revealed a significant trial ($F_{1,13} = 7.22$, $p = 0.02$) and step effect ($F_{1,13} = 18.55$, $p < 0.001$) with higher MoS at TD Pert and TD Reco1L for $T2_{Pre}$ compared to $T1_{Pre}$ and TD Reco1L compared to TD Pert for both trials (see figure 2).

Insert figure 1

Insert figure 2

Discussion

We aimed to examine potential differences in retention of improvements in gait stability over 14 weeks in response to single- and multiple-dose trip-like gait perturbation training. The results partly support our hypothesis that higher retention effects may be attained through a higher perturbation dose as significant improvements in the reactive response to an unexpected trip-like gait perturbation after 14 weeks were found only in the group that completed eight perturbation trials (group MULTIPLE). No retention effects were found after a single trip exposure (group SINGLE), indicating that there is (under our conditions) a threshold for perturbation dose for provocation of adaptive changes in the human neuromotor system over several months.

Margin of stability at TD of the perturbed step and first recovery step was significantly less negative (more stable body configuration) after 14 weeks compared to the initial session in group MULTIPLE (eight perturbation trials). These results are in accordance with our earlier findings (Epro et al., 2018b), showing retention in gait stability improvements over 14 weeks following a single bout of trip-like gait perturbations in older women. Thus, although middle- and older-aged adults have a higher fall risk, they are still able to improve their reactive responsiveness through repeated exposure to unexpected perturbations and retain those improvements over a period of months. Since for single trip exposure we found no significant differences in MoS between the two measurement time points for any of the analysed steps it is likely that a single perturbation may have been too low to facilitate learning effects lasting for several months. This supports previous findings seen in slipping, showing that in younger adults a single slip exposure without additional sessions was not sufficient to yield retention effects in gait stability over four months (as compared to a higher perturbation dose comprising 24 slips; Bhatt and Pai, 2009). Taken together, these results indicate that perturbation dose must exceed a threshold in order to induce retention of improvements in gait stability over several months acquired during single-session treadmill training.

Repetitive exposure to unexpected trip-like perturbations may promote adaptation of the central nervous system to sudden mechanical changes in the environment. The current study was focused on reactive (feedback-driven) response to unexpected gait perturbations. Even though predictive (feedforward-driven) adjustments of gait may occur after repeated perturbations (Bierbaum et al., 2010; McCrum et al., 2016), we found no differences in dynamic stability parameters at TD of the step immediately before the perturbation and baseline walking for any of the perturbation trials (unpublished data), indicating that the observed gait stability improvements were predominantly feedback-driven. Whether the observed adaptive changes to the perturbations in group MULTIPLE are driven foremost by the modulation of spinal reflexes as previously seen in human infants (Lam et al., 2003; Pang et al., 2003) or by automatic supraspinal postural responses (Jacobs and Horak, 2007) cannot be determined from the current findings, though the issue should be examined in future investigations.

In addition, when analysing the initial first two perturbation trials in group MULTIPLE, MoS was significantly improved in the second compared to the first trial. Therefore, we could assume short-term adaptive changes after single trip exposure in group SINGLE without possibly affecting retention by adding another perturbation.

Finally, our finding that single trip exposure in group SINGLE failed to facilitate adaptive changes in reactive gait stability over 14 weeks does not support previous results seen for slipping (Liu et al., 2017). This group reported significant improvements in reactive stability, and hence a reduction in laboratory falls, 12 months after a single gait slip. Contradictions between findings requiring further investigation may be related to the different perturbation types (tripping vs. slipping), numbers of initially reported falls and ages of participating subjects (middle-aged vs. community-dwelling older).

We have to acknowledge that our current protocol might not fully replicate a real-life trip situation and that this may possibly restrict generalisability of the observed gait stability improvements. However, despite the fact that gait-trip mechanics are highly variable in nature, the common consequence of stumbling in real-life situations may require similar postural corrections to regain balance to those observed in our perturbation setup (i.e. effectively increasing base of support; Epro et al., 2018a; McCrum et al., 2014; Süptitz et al., 2013). Although the applied perturbation magnitude was equal among all analysed participants, the effect of the perturbation on MoS in absolute terms appeared to differ slightly between groups (on average by 4 cm; see figure 1), though this difference did not reach statistical significance ($p = 0.78$). Therefore, one might argue that the failure of retention for group SINGLE may be due to an initially lower effect on stability. However, on analysing the relationship between the MoS during the initial perturbation and its relative change after 14 weeks by including our previous data on older adults (Epro et al., 2018b; total $n = 23$), we found no significant correlation ($r = 0.28$; $p = 0.21$) and hence are confident that the observed group differences for retention are predominately related to perturbation dose rather than its initial effect on stability. Finally, the number of analysed subjects is relatively low (n = 14 for MULTIPLE; n = 9 for SINGLE), possibly reducing the potential for determining significant retention effects in MoS (this is reflected in low effect sizes for group SINGLE: Cohen's d = 0.33 and 0.29 for TD Pert and Reco1L respectively). However, since the observed retention effects for group MULTIPLE were large (on average about 80% improvement in MoS) though the group was quite small in size, we are confident that the low sample size for group SINGLE is not the primary driver for the lack of functional retention effects for this group.

In conclusion, our results provide evidence for the existence of a threshold for perturbation dose if retainable adaptive changes are to be provoked in the human neuromotor system. We found that brief exposure to several unexpected trip-like gait perturbations, but not a single trip, can facilitate retention in reactive gait stability improvements over months, indicating that a finite number of perturbations may be required for retention of fall-resisting skills over several months.

Disclosure of Interest

The authors declare no conflicts of interest.

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Figure 1: Margin of stability (MoS) during unperturbed walking (Base), for touchdown at perturbation (Pert) and for the following six recovery steps after the perturbation (Reco1L-Reco6R) in group MULTIPLE (*n* = 14) and group SINGLE (*n* = 9). Data are given for the first trip-like gait perturbation trial at the initial training session and post 14 weeks ($T1_{Pre}$ and $T1_{Post14w}$, respectively). Values are expressed as means with SD error bars. T_M represents a statistically significant time point effect for group MULTIPLE ($p < 0.01$). L: Left leg. R: Right leg.

Figure 2: Margin of stability (MoS) during unperturbed walking (Base), for touchdown at perturbation (Pert) and for the following six recovery steps after the

perturbation (Reco1L-Reco6R) in group MULTIPLE (*n* = 14), after the first ($T1_{Pre}$) and second ($T2_{Pre}$) trip-like gait perturbation trials at the initial training session. Values are expressed as means with SD error bars. * represents a statistically significant trial effect ($p < 0.05$). # represents a statistically significant difference to Pert ($p < 0.001$). L: Left leg. R: Right leg.

Supplementary material 2: Experimental setup for the assessment of the recovery response following the first unexpected trip-like gait perturbation trial during treadmill walking (1.4 m s^{-1}) for a typical participant.