Improving Trip- and Slip-Resisting Skills in Older People

Improving Trip- and Slip-Resisting Skills in Older People: Perturbation Dose Matters

Kiros Karamanidis[1], *Gaspar Epro*[1], *Christopher McCrum*[2], *and Matthias König*[1]

[1]Sport and Exercise Science Research Centre, School of Applied Sciences, London South Bank University, London, UK; and [2]Department of Nutrition and Movement Sciences, NUTRIM School of Nutrition and Translational Research in Metabolism, Maastricht University Medical Centre+, Maastricht, The Netherlands

KARAMANIDIS, K., G. EPRO, C. MCCRUM, and M. KÖNIG. Improving trip- and slip-resisting skills in older people: perturbation dose matters. *Exerc. Sport Sci. Rev.*, Vol. 48, No. 1, pp. 40–47, 2020. *Aging negatively affects balance recovery responses after trips and slips. We hypothesize that older people can benefit from brief treadmill-based trip and slip perturbation exposure despite reduced muscular capacities, but with neuropathology, their responsiveness to these perturbations will be decreased. Thus, to facilitate long-term benefits and their generalizability to everyday life, one needs to consider the individual threshold for perturbation dose.* **Key Words:** falls, balance, perturbation training, gait stability, neurological disorders, locomotion, aged

Key Points

- Aging and neuropathology negatively affect balance recovery responses after sudden gait perturbations such as trips and slips.
- Older adults can adapt and retain trip- and slip-resisting skills through brief exposure to repetitive treadmill gait perturbations despite age-related muscular changes, but pathology of the sensory and neuromotor systems reduces the responsiveness to such practice.
- To facilitate trip- and slip-resisting skills and long-term reduction in fall risk, there is a need to consider the individual threshold for practice dose (number of perturbations).

INTRODUCTION

Balance control during human biped locomotion in constantly changing environments requires a continuous correspondence between perceptual information and motor responses. This is achieved by the central nervous system governing the musculoskeletal system according to visual, vestibular, and proprioceptive feedback received from the environment (*e.g.*, terrain and walking surface) in which the movement occurs. Locomotor adaptability resulting from these systems is essential for successful and safe mobility. Although this process can be accomplished easily by healthy young adults, it becomes more demanding and less effective with increasing age, especially in the presence of neurological disorders (*e.g.*, Parkinson, stroke, vestibulopathy), which coincides with the increased risk of falls in these groups (1). Environmental perturbation-related falls while walking due to trips or slips are responsible for about 60% of outdoor falls among older adults (2).

Long-term exercise interventions over several months aimed at increasing older adults' balance or muscle strength have been shown to be effective in reducing fall risk (3). However, according to the concept of training specificity, the motor skills required for avoiding a trip- or slip-related fall may be improved most effectively and efficiently (within several training sessions) with skill-specific training (4), which represents a departure from conventional long-term fall prevention interventions. Treadmill-based perturbation training using cable-trip systems (5–8) or belt accelerations/decelerations (9–11) can simulate slip- or trip-like perturbations and trigger error-driven motor learning in the control of postural balance. The perturbation-induced motor error stimulates the central nervous system via sensory feedback to adapt the motor programs relevant for gait and balance to increase the system's robustness to similar future balance disturbances, a process that includes acquisition, retention, and generalization of the fall-resisting skills. This has been supported by evidence that treadmill-based trip perturbation training targets specific balance recovery mechanisms that may be beneficial when an actual trip is experienced during daily life (12). An advantage of the treadmill in relation to overground setups is that predicting when a perturbation will be applied is more difficult, which ensures that mainly reactive balance control strategies are involved. Furthermore, practice dose (defined as the total amount of perturbation trials experienced over a given exercise period) and perturbation intensity can be easily and

Address for correspondence: Kiros Karamanidis, 103 Borough Road, London SE1 0AA, UK (E-mail: k.karamanidis@lsbu.ac.uk).

Accepted for publication: August 19, 2019.
Editor: Roger M. Enoka, Ph.D.

0091-6331/4801/40–47
Exercise and Sport Sciences Reviews
DOI: 10.1249/JES.0000000000000210

quickly manipulated in a safe, controlled environment. This is of particular relevance for the conceptualization of fall prevention interventions because the hypothesis of the dose-response relationship implies that adaption may not be directly related to the applied practice dose (*i.e.*, *non*linear relationship) and that a dose threshold exists beyond which any additional stimuli may not induce further changes. Due to the growing body of evidence that fall prevention interventions using treadmills to deliver large postural disturbances (relatively high perturbation magnitude) seem to be both effective and efficient for improving fall-resisting skills, there also is a critical need to identify the most effective practice dose (4). It is quite likely that the extent for immediate (within the same training session) or long-term gains and, hence, the effectiveness of the applied practice dose will depend on the specific skills and neuromotor capacities of an individual or population.

This review hypothesizes that older people can benefit from brief treadmill-based trip and slip perturbation exposure despite reduced muscular capacities, but with neuropathology, their responsiveness to these perturbations will be decreased, reflecting a rightward shift in the practice dose-response relationship (Fig. 1). The perturbation practice dose-response relationship here refers to the relation between the number of perturbations and long-lasting changes in balance responses generalizable to daily life trip and slip situations, for which we propose that a critical threshold exists. Note that our hypothesis includes both middle-aged (*i.e.*, about 40–59 yr) and older adults (*i.e.*, ≥60 yr), covering the ages in which various age-related changes have been observed (we have used 60 yr as a cutoff as this is deemed appropriate by the United Nations for classifying older adults in international contexts) (13). Our recent data suggest that the potential for improvement after repeated perturbations is independent of changes in lower limb muscle-tendon unit capacities, and we hypothesize here that, as opposed to the general age-related decline in muscular capacities, neurological deterioration (often age related) in which the sensory inflow or motor control is affected, may lead to a decreased responsiveness to treadmill-based perturbations (Fig. 1). As such, in neuropathology, lower practice doses possibly limit the retention and the generalizability of the beneficial adaptations (the extent to which adaptations are maintained over time and can be translated to improvements in performance in daily life trip and slip situations). This would support our view that disruptions in locomotor control, stability, and learning (*e.g.*, adaptation rate and magnitude) may be more apparent in sensory or neuromotor decline than in age-related deterioration of muscular capacities. Because of the majority of falls occurring as a result of trips and slips during walking, as well as the practical and feasibility-related advantages of a treadmill-based setup, this review focuses on information derived from studies of balance control and training from treadmill trip and slip perturbations in both healthy adults and those with neurological disorders affecting the sensory or neuromotor systems.

MAINTAINING BALANCE AFTER TRIPS AND SLIPS

Human walking is partly controlled by central pattern generators, which are spinal cord neurons, providing near autonomous control of basic locomotor rhythms (14). Afferent feedback to

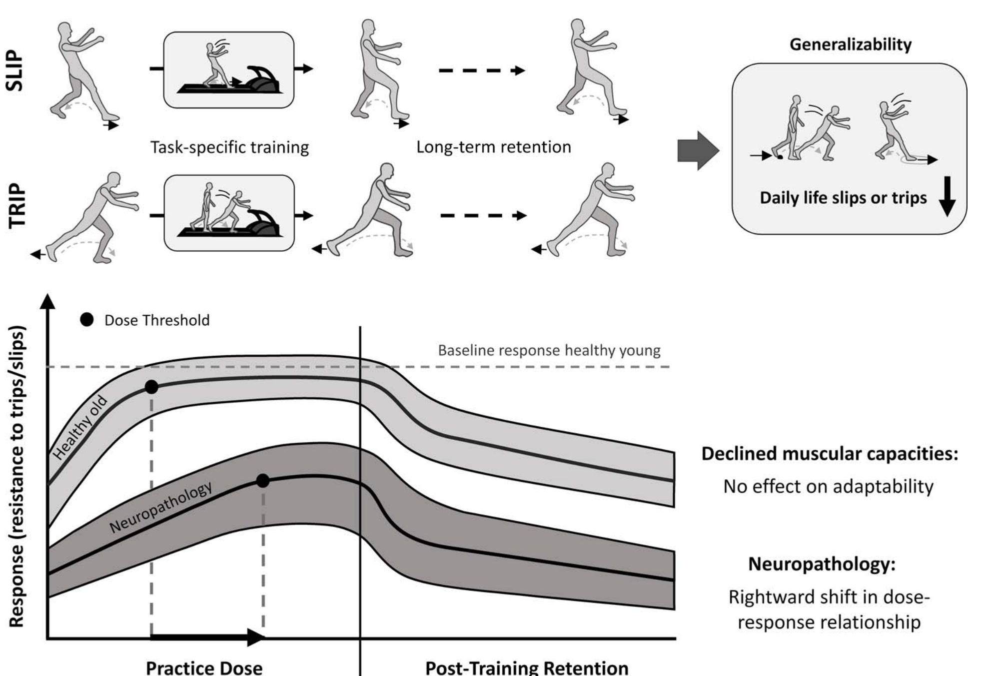

Figure 1. Schematic illustration of the proposed hypothesis: a brief exposure to high magnitude gait perturbations, which mimic real-life slip- or trip-like perturbations (task-specific training), can stimulate long-term adaptive changes (long-term retention) within the locomotor system. These changes lead to improved resistance to treadmill trips/slips and reduced incidence of trip/slip falls in daily life situations in older adults, given that a critical threshold (dark circle) for perturbation practice dose (number of perturbation trials) is reached. These improvements in fall-resisting skills can be partly retained in healthy older adults over several months up to years without additional training (posttraining retention). In neuropathology, in which the sensory systems or motor control is affected, it is proposed that, due to a rightward shift in the practice dose-response relationship for perturbation training, a greater total amount of perturbation trials experienced over a given exercise period will be required to reach the critical practice dose threshold to stimulate beneficial improvements in fall-resisting skills. Experiencing perturbation practice dose below the critical threshold will lead to a lower improvement and generalization of the fall-resisting skills, whereas additional stimuli beyond this threshold have no further benefit (steady state).

the spinal cord allows reactive adjustments, whereas feedback to the supraspinal structures facilitates predictive adjustments in the locomotor patterns (14), potentially aiding postural balance and stability during locomotion. When gait stability is unexpectedly disturbed, the neuromotor system applies a series of reactive corrections to reestablish postural equilibrium. In mechanical terms according to Hof (15), this can be achieved by adjusting the application of force to the ground, by counterrotating body segments around the center of mass (CoM) or by applying forces other than the ground reaction force (*e.g.*, by grasping a handrail).

In case of an unexpected slip or trip during gait, the relation between the body's CoM and the base of support is suddenly disrupted either by a disturbance of the swing limb (trip) or unwanted displacement of the stance limb (slip). Because of the high displacement of the CoM, it is not surprising that during tripping, a large anterior step is typically required to recover balance, initiated either by the perturbed leg when the disturbance occurs early in the swing phase (raising the perturbed limb over the obstacle; elevating strategy) or by the contralateral leg when the disturbance occurs later in swing (placing the perturbed limb quickly on the ground, aborting the step, and stepping with the unperturbed limb; lowering strategy) (16). In both cases, the leg taking the compensatory recovery step needs to rapidly move forward (in particular via high moment generation by the hip flexors) to be able to generate a moment at landing to effectively counteract the forward angular momentum of the trunk (17). The joint moment generation of the support limb (trailing leg) also plays an important role, as during the push-off, the moments generated by the ankle plantar flexors and knee extensors, as well as the hip extensors, provide enough time for clearance and positioning of the stepping limb (leading leg) and counteract the forward angular momentum of the CoM (18). In contrast, slipping can occur in multiple directions to one or both limbs. However, slips leading to an anteriorly directed displacement of the stance limb resulting in a backward loss of balance have been most often studied. Once a backward balance loss is initiated, the primary motor response is to act against the sliding motion of the foot by generating knee flexion and hip extension joint moments in the slipping (leading) limb to minimize the vertical descent of the body (19). In addition, a compensatory step by the trailing limb posterior to the CoM is required to recover balance (20), initiated after the onset of the slipping limb motor responses by generating an extension moment at the hip and flexion moment at the knee joint in the trailing limb to cause foot clearance and to interrupt the anterior displacement of the foot after toe-off, followed by a knee extension moment to lower the trailing limb onto the ground (21). It can be concluded that both slipping and tripping typically require the effective use of dynamic stability control mechanisms (*i.e.*, counterrotation of body segments and adjusted application of ground reaction forces), although the contribution of each to balance recovery after trips and slips likely differs.

BALANCE CONTROL DURING TRIPS AND SLIPS IN HEALTHY AGING AND NEUROPATHOLOGY

It is widely acknowledged that the aging process leads to a general deterioration of the neuromuscular system, including a gradual loss in motor neurons and impaired muscle activation, leading to loss in muscle mass and decreases in strength and power (22). These degradations are frequently related to diminished locomotor performance. Age-related deficiencies in the recovery from many kinds of sudden balance loss have been demonstrated, including tripping and slipping (5,23,24), and can already be detected in middle age (5). Epidemiological studies showing an increasing fall risk across the adult lifespan also highlight the need for targeted fall prevention strategies in these age groups (25). In previous studies, we found a significant but only moderate association between leg-extensor muscle-tendon unit capacities (muscle strength, tendon stiffness), in particular of the triceps surae muscle, and the ability to increase the base of support after a sudden anterior loss of balance from forward-leaning positions and unexpected treadmill trip perturbations (7,26). These findings may provide an explanation for the reduced ability to generate a large anterior balance recovery step with aging (5), and align with other earlier studies showing that the diminished ability to regain stability during perturbed walking is related to older adults' reduced ability to generate appropriate joint moments in the trailing limb during push-off (18). Like gait-trip perturbations, previous studies have demonstrated that muscle weakness of the lower limbs seems to be associated with the frequency of laboratory-based slip-like falls in older adults (27).

Although the muscle activity patterns (sequencing and timing) in the lower limbs after trip and slip perturbations are similar in young and older adults, the magnitude and rate of development of muscle activity are considerably lower in older adults (23,28), indicating deficits in the neuromuscular control and reactive response (including reaction time) in older adults during the recovery task. In line with this, Arampatzis *et al.* (29) demonstrated that a less effective motor response during the push-off phase of the trailing limb was related to unsuccessful recovery from a forward fall, irrespective of leg-extensor muscle-tendon unit mechanical properties, which emphasizes the importance of neuromuscular control for balance. This supports our view that a disruption in key functions of locomotor control for maintaining stability in middle-aged and older adults may arise predominantly from neuromotor decline rather than from age-related muscular changes.

Successful recovery from balance loss not only requires precise neuromuscular control but also requires accurate detection and processing of balance loss. One of the sensory systems providing important information for balance control is the vestibular system, which monitors angular and linear accelerations of the head in space (30). In our previous study in middle-aged adults, we exposed participants to trip-like perturbations via a cable system similar to our other studies (5,7,8,31). We found that, compared with healthy controls, people with unilateral vestibulopathy showed a diminished recovery response to the first unexpected perturbation and required at least six steps (vs four in controls) to recover stability (6) (Fig. 2B). Thus, next to the alterations described previously accompanied with aging (*i.e.*, altered neuromuscular control), these results indicate a potential role of the vestibular apparatus in postural corrections during an unexpected perturbation to gait. Other studies using slightly different paradigms that still require the same recovery mechanisms (rapid increase in the base of support) also provide some insight. For example, Moreno Catalá *et al.* (32) found that people with Parkinson disease, as opposed to healthy controls,

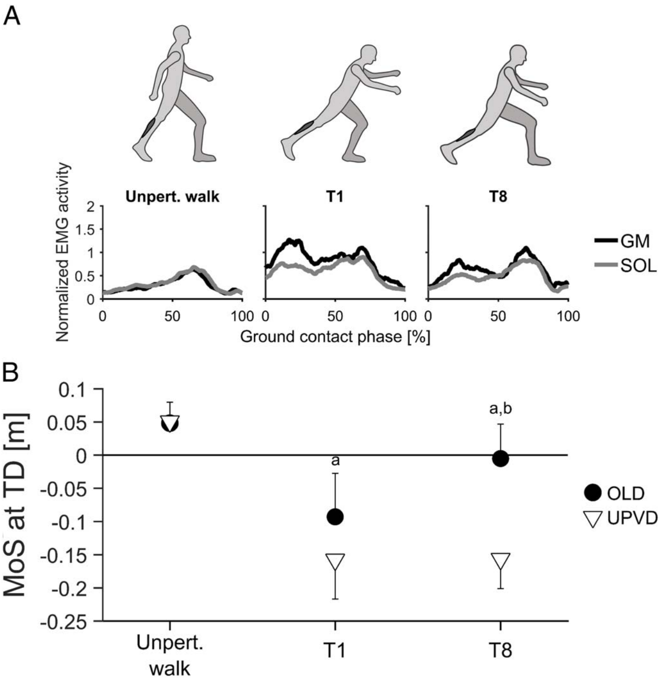

Figure 2. A. Electromyographic (EMG) activity of m. gastrocnemius medialis (GM) and m. soleus (SOL) during the ground contact phase during unperturbed walking and of the perturbed step (trailing limb) during the first (T1) and eighth (T8) perturbation trials of a single perturbation training session in a group of healthy older adults ($n = 22$). EMG activity was normalized to the maximal activity during unperturbed walking for the corresponding muscle. B. Margin of stability (MoS; mean values and SD) at touchdown (TD) of the perturbed leg in the first (T1) and eighth (T8) trials of a single perturbation training session in a group of healthy older adults (OLD; $n = 22$) and middle-aged unilateral peripheral vestibular disorder patients (UPVD, $n = 13$). Note that whereas healthy middle-aged adults show rapid adaptation to the repeated perturbation exposure, these adaptations seem dependent on an intact sensory inflow. [a]Statistically significant difference between the groups OLD and UPVD ($P < 0.05$). [b]Statistically significant difference to T1 for group OLD ($P < 0.05$). A. Bottom panel: [adapted from (7). Copyright © 2018 the American Physiological Society. Used with permission.] B. [Adapted from (6). CC BY-NC 4.0.]

were not able to significantly increase their base of support after a sudden change in ground surface compliance during walking. In people who have had a stroke, anterior surface translation perturbations (initiating backward balance loss similar to a slip) to stance result in more falls compared with age-matched controls and young healthy adults (71% of trials vs 0% in the other groups), and patients have poorer stability control during recovery and require more recovery steps (33). In summary, aged populations and, in particular, multiple neurological patient groups seem to have a reduced ability to cope with a sudden, unexpected mechanical perturbation to balance and gait predominately because of their inability to rapidly increase the base of support.

IMPROVING TRIP- AND SLIP-RESISTING SKILLS

It is well established that the human neuromotor system can adapt its motor behavior to intrinsic (*e.g.*, growth, muscle fatigue) and extrinsic changes (*e.g.*, changes in the mechanical environment), creating a complex interaction between sensory feedback information from the periphery and motor output (34). Unexpected perturbations to balance will provoke involuntary sensory prediction errors, which may not be mitigated solely by volitional corrective motor responses and hence stimulate the central nervous system to reorganize its internal representation of the body within the mechanical environment (35). Previous studies have indeed demonstrated significant improvements in reactive gait stability after repeated exposure to unexpected slip- or trip-like perturbations (24 or 8 repetitions, respectively) not only in young and middle-aged adults (6,31) but also in older adults, that is, 60–90 y (7,24). Notably, we recently found remarkable adaptations in reactive gait stability in healthy older adults (mean age ± SD, 65 ± 7 yr) to eight repeated unexpected treadmill-based trip perturbations due to a refined neuromuscular control (Fig. 2) (7). Interestingly, participants' adaptation potential to these perturbations was independent of their triceps surae muscle-tendon unit capacities (7) and similar to that reported for middle-aged adults in the same laboratory setup (31). These results support our hypothesis that an age-related degeneration of muscular capacities seems not to affect one's ability to adapt and improve such fall-resisting skills after repeated gait perturbations (7). Moreover, when considering the trial-to-trial adaptation over the eight trip perturbations, we were able to demonstrate a gradual increase in reactive gait stability with increasing perturbation practice dose in middle-aged and older adults, with no further improvements after only four to five perturbation trials (6,7). Combined with the results seen for overground slip perturbation training showing similar rapid improvement (*i.e.*, "single trial effect") and plateauing of training effects after merely a few slip trials in healthy young and older adults (24), these findings support the notion that a small number of slip or trip perturbation trials are sufficient to facilitate large refinements in the locomotor-balance control system, irrespective of age. Nevertheless, whether the adaptation rate and amount, and, hence, the perturbation dose-response relationship, are comparable across the adult lifespan remains unclear and needs further investigation, and a lack of knowledge regarding the dose-response relationship in exercise-based fall prevention has been highlighted recently (4,36).

Given the fact that successful motor learning depends on the function of the neuromotor system, this review proposes the hypothesis that difficulties in improving fall-resisting skills will be seen when the normal flow of information within the nervous system is altered because of pathology (Fig. 1). In our previous study in unilateral vestibulopathy using eight repeated trip perturbations on a treadmill as described, we found significant improvements in reactive gait stability during the perturbed step in healthy age-matched controls but not in the patients with vestibulopathy (Fig. 2B) (6). This suggests that a lack of accurate vestibular sensory feedback may result in diminished locomotor adjustments and may negatively affect the modification of internal models of the external environment (35), which could lead to diminished corrections and adaptations of the reactive response to repeated perturbations. However, we found improvements in the number of steps required to recover balance in the vestibulopathy group, although not to the same extent as the healthy age-matched controls. Based on these findings, we propose that patients with vestibulopathy can still make improvements in their balance recovery responses, but an increased practice dose (by increasing the total amount of perturbation trials experienced over a given exercise period) may be needed. Looking beyond the sensory systems themselves, another structure that plays a critical role in motor control and sensory integration is the cerebellum. One study (37) examined how patients with cerebellar lesion (n = 5; age range, 20 to 56 yr) and age-matched controls deal with 60 repeated, sudden deceleration-acceleration perturbations during treadmill walking. In line with our observations in vestibulopathy, patients improved their response over time, with fewer multistep recoveries toward the end of the session, but these improvements were faster, less variable, and more apparent in the healthy control group.

Although not necessarily directly influencing sensory input, other neurological disorders that disrupt sensory integration or neuromotor control could be expected to influence the adaptation to perturbations such as in stroke. Nevisipour *et al.* (38) reported that in people who have had a stroke, a training session of 15 posterior treadmill translation perturbations during stance resulted in reduced trunk flexion during recovery from a similar but untrained perturbation, indicating a training-related improvement, but trunk flexion velocity, reaction time, step duration, step length, and stability did not improve. Bhatt *et al.* (39) applied repeated anterior surface translation perturbation (initiating backward balance loss) to stance in people who have had a stroke with both higher and lower motor impairment. Both groups improved in their ability to cope with the perturbations (fewer falls and better stability control), but there was a slower rate of adaptation over the trials in people with more severe motor impairment. Consistent with our hypotheses, these data suggest that the response to training is affected by neuromotor function and that there is a need to consider the individual threshold for practice dose. Although not applying trip or slip perturbations, both Moreno Catalá *et al.* (32) and Martelli *et al.* (40) have demonstrated a lack of improvement in the balance recovery responses of people with Parkinson disease after repeated perturbations (six sudden surface compliance changes or 72 anteroposterior and mediolateral waist pulls, respectively) during gait. These findings indicate that with neurological disorders, it may be difficult to stimulate the improvements of fall-resisting skills that are commonly observed in healthy middle-aged and older adults as described above, at least within a single gait perturbation training session or with a similar number of perturbation trials. In summary, there are some early indications that slip- or trip-like perturbations on the treadmill would potentially provide sufficient stimulus to trigger improvements in fall-resisting skills in middle-aged or older adults who have had a stroke, with vestibulopathy, and with cerebellar lesions, although impairment severity will likely influence both the tolerance to perturbations and the adaptive response to the perturbations. This suggests that the perturbation practice dose-response relationship is shifted to the right, but it could be harder to reach sufficient practice doses within single training sessions to trigger substantial adaptations (Fig. 1). Further investigation is needed to detect thresholds for practice dose required to induce robust gait modifications (indicated by a plateau in learning effects) as seen for healthy middle-aged and older adults, which also may have important consequences on their retention or generalizability to different conditions.

RETENTION AND GENERALIZABILITY OF IMPROVED TRIP- AND SLIP-RESISTING SKILLS

It is well known that adaptation of locomotion in response to repeated perturbation exposure can occur quite rapidly in healthy middle-aged and older adults, even within a single treadmill perturbation training session consisting of only a few perturbation trials. Importantly, for overground walking, previous slip perturbation studies have demonstrated that the acute adaptations in reactive gait stability acquired during a single slip perturbation training session (up to 24 slips) can be partly retained for both short-term (a few weeks) and long-term (up to 12 months) periods by older adults in the same laboratory settings (41–43). One of our gait-trip treadmill perturbation studies (eight trips at baseline, eight trips at 14 wk) supports these findings, as we found that the improved recovery responses can be partly retained over 1.5 yr in older adults (65 ± 7 yr) (8), but that these improvements decay over time in this age group (Fig. 3). This suggests that even at a higher age, repeated exposure to gait perturbations that mimic real-life slips or trips seems to be an appropriate stimulus for the human central nervous system to improve and retain balance control strategies specific to the practiced perturbation type. Enhancing triceps surae muscle-tendon unit capacities through controlled resistance exercise over 1.5 yr did not lead to further meaningful improvements in older adults' recovery response after a trip (Fig. 3) (8). Thus, older adults seem to benefit more from specific exposure to unexpected gait perturbations than from improving presumed fall risk-related factors (*i.e.*, muscle strength), as this alone seems to result in sufficient improvement in performance of the targeted task.

The identified decay in reactive gait stability improvements over time (8) raises the question whether this decay is influenced by the person's age. The comparison of different studies from our laboratory on retention over several months indicates lower retention of adaptations in older compared with middle-aged adults for the same treadmill trip perturbation paradigm (8,31). Future studies should therefore investigate whether

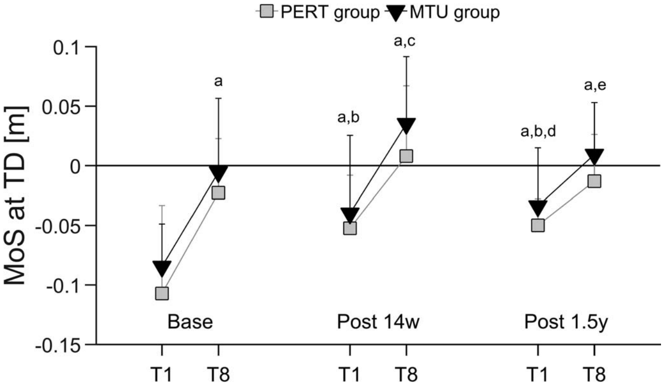

Figure 3. Margin of stability (MoS; mean values and SD) at touchdown (TD) of the perturbed leg during the first (T1) and eighth (T8) perturbation trials of a single perturbation training session (eight unexpected gait-trip perturbations) at baseline (Base), post 14 wk (Post 14 wk) and post 1.5 yr (Post 1.5 yr) measurement time points in a group of older female adults experiencing trip-gait perturbation training (PERT group; n = 13) and a second group of older female adults who, in addition, underwent a triceps surae muscle-tendon unit (MTU)–specific exercise over 1.5 yr (MTU group; n = 12). Note that the training-induced enhancement of the triceps surae MTU capacities did not benefit the recovery response from a sudden trip. [a]Statistically significant difference to T1Base (P < 0.05). [b]Statistically significant difference to T8Base (P < 0.05). [c]Statistically significant difference to T1Post14 wk (P < 0.05). [d]Statistically significant difference to T8Post14 wk (P < 0.05). [e]Statistically significant difference to T1Post1.5 yr (P < 0.05). [Adapted from (8). Copyright © 2018 the American Physiological Society. Used with permission.]

long-term retention (*i.e.*, several months or years) of exercise-induced improvements in gait stability control may diminish across the adult lifespan.

Next to aging, the amount of practice seems to affect various aspects of learning. Specifically, there is a growing body of evidence that to achieve such long-lasting refinement of balance control strategies, certain practice doses may be required. For instance, even though experiencing only one overground slip during walking can facilitate long-term retention of the acquired fall-resisting skills in older adults, these effects were approximately 50% less than after interventions with higher practice doses (*i.e.*, 24 slip perturbations) (42). Furthermore, specific ancillary "booster" sessions consisting of only a single slip have been found to further aid to these superior retention effects (43). In agreement with these results, we recently found evidence of a critical threshold for the amount of treadmill-based trip-like perturbation trials required to provoke retainable adaptive changes in the human neuromotor system (31). Specifically, we found a retention of reactive gait adaptations over several months in healthy middle-aged adults only when they were exposed to repeated (eight) gait-trip perturbations and not if they only experienced a single perturbation (31). Thus, whereas brief exposure to treadmill-based gait perturbations appears to be sufficient to achieve acute improvements in fall-resisting skills in aging, retention of learned skills seems to require a minimum perturbation practice dose facilitating robust gait modifications (*i.e.*, reaching a plateau in the dose-response relation).

To have a beneficial impact on daily life, these treadmill-based perturbation training paradigms must result in fall-resisting skills that can positively benefit recovery from an actual trip or slip. At least partial generalizability of adaptations to repeated treadmill-delivered trip or slip perturbations to the recovery response after an untrained trip/slip during overground walking has been reported (9,44). Moreover, one study could show reductions in trip-related fall incidences (but not all cause falls) during everyday life after experiencing over a 2-wk period four sessions of treadmill-based trip perturbation training (12). When combining these results with recent findings in younger adults (10,11) indicating an increased generalizability of treadmill perturbation training effects (*i.e.*, improved transfer to overground slips) with higher practice dose, it can be suggested that one primary driver of a person's ability to cope with gait perturbations during everyday life may be the total amount of perturbation trials experienced in the laboratory. However, there seems to be a certain threshold for perturbation practice dose (>24 perturbation trials), beyond which additional stimuli do not further increase transfer to the overground condition in healthy older adults (45), indicating a critical optimum in the perturbation practice dose-response relationship for generalizability to daily life situations.

It is important to highlight that there is currently little information in the literature regarding the retention and generalizability of fall-resisting skills in neurological populations. Using multidirectional perturbations to stance, Van Duijnhoven *et al.* (46) found that people who have had a stroke could improve the percentage of trials recovered in a single step over 5 wk of training, an effect that was retained 6 wk postintervention. These findings indicate an intact ability of retaining perturbation exposure-mediated adaptations in people who have had a stroke if the number of practice sessions is sufficiently high enough, supporting our proposed hypothesis. In line with this, some preliminary studies on long-term perturbation training over several months in Parkinson and stroke have shown promising (but often not significant, potentially due to small samples) effects on daily life fall incidences, implying a longer benefit and generalizability of the training (for a review, see (47)), but no study known to the authors has directly assessed this in a similar manner to the studies discussed in healthy middle-aged and older adults. Given the potential deficits in gait stability and adaptability in response to repeated perturbations in neurological populations (rightward shift in the practice dose-response relationship), it is reasonable to assume that retention and generalizability of such improvements will also be affected negatively (Fig. 1).

Our proposed hypothesis of a minimum required perturbation practice dose to most effectively facilitate learning (*i.e.*, adaptation, retention, and generalizability) in the reactive balance control system requires consideration of the tolerability of training for older adults. It may be that the minimum required dose exceeds the tolerance threshold of participants, leading to anxiety or inability to physically cope with the perturbations. This may be of particular importance when using this training approach with frail or clinical people or groups. One possible solution might be to progressively increase the complexity, unexpectedness, or magnitude of perturbations to initially increase training tolerance so that the minimum required dose can be achieved after a certain period. Such approaches recently have been shown to induce significant improvements in reactive stability control in community-dwelling older adults (48,49).

One obvious limitation for the field is that conducting large-enough trials to have enough statistical power to detect the effects of such training on daily life fall incidences will need high financial and high time commitments. The required sample size would increase even further if researchers wished to reliably evaluate the effects on specific types of falls (*e.g.*, falls due to slips or trips), to increase the number of the specific type of fall of interest in the assessed sample. However, it is this information that would provide more definitive answers to questions regarding the most effective interventions. For instance, whereas remarkable reductions in trip-related fall incidences (but not all cause falls) after experiencing four sessions of treadmill-based trip perturbation training within a 2-wk training period have been observed by one study (12), this task-specific transfer to everyday life could not be observed in slipping (50), potentially because of the low statistical power for this outcome of the study. In this context, it is important to note that the present review does not allow for a general conclusion regarding the optimum number of perturbations needed to facilitate retainable and transferable fall-resisting skills in older adults, as differences in perturbation paradigms (*i.e.*, perturbation types and magnitude) may also affect the dose-response relationship. For these reasons, steps toward aligning and standardizing perturbation training protocols and methodologies, as well as assessment methods are critical to facilitate larger, multicenter, collaborative studies.

CONCLUSIONS

Healthy middle-aged and older adults can benefit from specific treadmill slip and trip perturbation training interventions triggering large balance recovery responses (*i.e.*, high perturbation magnitudes), regardless of lower limb muscle-tendon unit capacities. Neuropathology in aging appears to disrupt locomotor control, stability, and learning, leading to a higher risk of falls in these populations and, more notably, resulting in a decreased responsiveness to treadmill-based perturbations. We propose that a critical threshold for perturbation dose (number of perturbation trials) exists to facilitate long-term adaptive changes and their generalizability to everyday life situations in older adults. This implies that retention of adaptations to perturbation exposure in older people with neuropathology can be achieved if the number of perturbation trials or training sessions fulfills their increased need for training exposure, due to a rightward shift in the practice dose-response relationship. As such, a longer period of perturbation training will be required to stimulate beneficial improvements in fall-resisting skills in older adults with neurological impairments.

References

1. Homann B, Plaschg A, Grundner M, et al. The impact of neurological disorders on the risk for falls in the community dwelling elderly: a case-controlled study. *BMJ Open*. 2013; 3(11):e003367.
2. Luukinen H, Herala M, Koski K, Honkanen R, Laippala P, Kivelä S-L. Fracture risk associated with a fall according to type of fall among the elderly. *Osteoporos. Int.* 2000; 11(7):631–4.
3. Sherrington C, Fairhall NJ, Wallbank GK, et al. Exercise for preventing falls in older people living in the community. *Cochrane Database Syst Rev.* 2019; 1:CD012424.
4. Grabiner MD, Crenshaw JR, Hurt CP, Rosenblatt NJ, Troy KL. Exercise-based fall prevention: can you be a bit more specific? *Exerc. Sport Sci. Rev.* 2014; 42(4):161–8.
5. Süptitz F, Moreno Catalá M, Brüggemann GP, Karamanidis K. Dynamic stability control during perturbed walking can be assessed by a reduced kinematic model across the adult female lifespan. *Hum. Mov. Sci.* 2013; 32(6):1404–14.
6. McCrum C, Eysel-Gosepath K, Epro G, et al. Deficient recovery response and adaptive feedback potential in dynamic gait stability in unilateral peripheral vestibular disorder patients. *Physiol. Rep.* 2014; 2(12).
7. Epro G, McCrum C, Mierau A, Leyendecker M, Brüggemann G-P, Karamanidis K. Effects of triceps surae muscle strength and tendon stiffness on the reactive dynamic stability and adaptability of older female adults during perturbed walking. *J. Appl. Physiol.* 2018; 124(6):1541–9.
8. Epro G, Mierau A, McCrum C, Leyendecker M, Brüggemann G-P, Karamanidis K. Retention of gait stability improvements over 1.5 years in older adults: effects of perturbation exposure and triceps surae neuromuscular exercise. *J. Neurophysiol.* 2018; 119(6):2229–40.
9. Grabiner MD, Bareither ML, Gatts S, Marone J, Troy KL. Task-specific training reduces trip-related fall risk in women. *Med. Sci. Sport Exerc.* 2012; 44(12):2410–4.
10. Yang F, Bhatt T, Pai Y. Generalization of treadmill-slip training to prevent a fall following a sudden (novel) slip in over-ground walking. *J. Biomech.* 2013; 46:63–9.
11. Yang F, Cereceres P, Qiao M. Treadmill-based gait-slip training with reduced training volume could still prevent slip-related falls. *Gait Posture.* 2018; 66:160–5.
12. Rosenblatt N, Marone J, Grabiner MD. Preventing trip-related falls by community-dwelling adults: a prospective study. *J. Am. Geriatr. Soc.* 2013; 61(9):1629–31.
13. Kowal P, Dowd JE. Definition of an older person. Proposed working definition of an older person in Africa for the MDS Project. *World Heal Organ.* 2001; 10(2.1):5188–9286.
14. Grillner S, Wallen P. Central pattern generators for locomotion, with special reference to vertebrates. *Annu. Rev. Neurosci.* 1985; 8:233–61.
15. Hof AL. The equations of motion for a standing human reveal three mechanisms for balance. *J. Biomech.* 2007; 40(2):451–7.
16. Eng JJ, Winter DA, Patla AE. Strategies for recovery from a trip in early and late swing during human walking. *Exp. Brain Res.* 1994; 102(2):339–49.
17. Grabiner MD, Koh TJ, Lundin TM, Jahnigen DW. Kinematics of recovery from a stumble. *J. Gerontol Med. Sci.* 1993; 48(3):M97–102.
18. Pijnappels M, Bobbert MF, Van Dieën JH. Push-off reactions in recovery after tripping discriminate young subjects, older non-fallers and older fallers. *Gait Posture.* 2005; 21(4):388–94.
19. Cham R, Redfern MS. Lower extremity corrective reactions to slip events. *J. Biomech.* 2001; 34(11):1439–45.
20. Maki BE, McIlroy WE. The role of limb movements in maintaining upright stance: the "change-in-support" strategy. *Phys. Ther.* 1997; 77(5):488–507.
21. Moyer BE, Redfern MS, Cham R. Biomechanics of trailing leg response to slipping—evidence of interlimb and intralimb coordination. *Gait Posture.* 2009; 29(4):565–70.
22. Aagaard P, Suetta C, Caserotti P, Magnusson SP, Kjær M. Role of the nervous system in sarcopenia and muscle atrophy with aging: strength training as a countermeasure. *Scand. J. Med. Sci. Sport.* 2010; 20:49–64.
23. Pijnappels M, Bobbert MF, Van Dieën JH. Control of support limb muscles in recovery after tripping in young and older subjects. *Exp. Brain Res.* 2005; 160(3):326–33.
24. Pai YC, Bhatt T, Wang E, Espy D, Pavol MJ. Inoculation against falls: rapid adaptation by young and older adults to slips during daily activities. *Arch. Phys. Med. Rehabil.* 2010; 91(3):452–9.
25. Donaldson LJ, Cook A, Thomson RG. Incidence of fractures in a geographically defined population. *J. Epidemiol. Community Health.* 1990; 44(3):241–5.
26. Karamanidis K, Arampatzis A, Mademli L. Age-related deficit in dynamic stability control after forward falls is affected by muscle strength and tendon stiffness. *J. Electromyogr. Kinesiol.* 2008; 18(6):980–9.
27. Ding L, Yang F. Muscle weakness is related to slip-initiated falls among community-dwelling older adults. *J. Biomech.* 2016; 49(2):238–43.
28. Tang P, Woollacott MH. Inefficient postural responses to unexpected slips during walking in older adults. *J. Gerontol A. Biol. Sci. Med. Sci.* 1998; 53(6):M471–80.
29. Arampatzis A, Karamanidis K, Mademli L. Deficits in the way to achieve balance related to mechanisms of dynamic stability control in the elderly. *J. Biomech.* 2008; 41(8):1754–61.
30. Kingma H, Van De Berg R. Anatomy, physiology, and physics of the peripheral vestibular system. In: Furman JM, Lempert T, editors. *Handbook of Clinical Neurology*. 3rd series Edition. New York: Elsevier B.V.; 2016. p. 1–16.
31. König M, Epro G, Seeley J, Catalá-Lehnen P, Potthast W, Karamanidis K. Retention of improvement in gait stability over 14 weeks due to trip-perturbation training is dependent on perturbation dose. *J. Biomech.* 2019; 84:243–6.
32. Moreno Catalá M, Woitalla D, Arampatuis A. Reactive but not predictive locomotor adaptability is impaired in young Parkinson's disease patients. *Gait Posture.* 2016; 48:177–82.
33. Salot P, Patel P, Bhatt T. Reactive balance in individuals with chronic stroke: biomechanical factors related to perturbation-induced backward falling. *Phys. Ther.* 2016; 96(3):338–47.
34. Scott SH. Optimal feedback control and the neural basis for volitional motor control. *Nat. Rev. Neurosci.* 2004; 5(7):532.
35. Shadmer R, Smith MA, Krakauer JW. Error correction, sensory prediction, and adaptation in motor control. *Annu. Rev. Neurosci.* 2010; 33:89–108.
36. Wang Y, Wang S, Bolton R, Kaur T, Bhatt T. Effects of task-specific obstacle-induced trip-perturbation training: proactive and reactive adaptation to reduce fall-risk in community-dwelling older adults. *Aging Clin Exp Res.* 2019; in press.
37. Rand MK, Wunderlich DA, Martin PE, Stelmach GE, Bloedel JR. Adaptive changes in responses to repeated locomotor perturbations in cerebellar patients. *Exp. Brain Res.* 1998; 122:31–43.
38. Nevisipour M, Grabiner MD, Honeycutt CF. A single session of trip-specific training modifies trunk control following treadmill induced balance perturbations in stroke survivors. *Gait Posture.* 2019; 70:222–8.
39. Bhatt T, Dusane S, Patel P. Does severity of motor impairment affect reactive adaptation and fall-risk in chronic stroke survivors? *J. Neuroeng. Rehabil.* 2019; 16(1):43.
40. Martelli D, Luo L, Kang J, Kang UJ, Fahn S, Agrawal SK. Adaptation of stability during perturbed walking in Parkinson's disease. *Sci. Rep.* 2017; 7(1):17875.
41. Pai YC, Yang F, Bhatt T, Wang E. Learning from laboratory-induced falling: long-term motor retention among older adults. *Age (Dordr).* 2014; 36(3):9640.

42. Liu X, Bhatt T, Wang S, Yang F, Pai YC. Retention of the "first-trial effect" in gait-slip among community-living older adults. *GeroScience*. 2017; 39(1):93–102.
43. Bhatt T, Feng Y, Pai YC. Learning to resist gait-slip falls: long-term retention in community-dwelling older adults. *Arch. Phys. Med. Rehabil.* 2012; 93(4):557–64.
44. Wang Y, Bhatt T, Liu X, et al. Can treadmill-slip perturbation training reduce immediate risk of over-ground-slip induced fall among community-dwelling older adults? *J. Biomech.* 2019; 84:58–66.
45. Lee A, Bhatt T, Liu X, Wang Y, Pai YC. Can higher training practice dosage with treadmill slip-perturbation necessarily reduce risk of falls following overground slip? *Gait Posture*. 2018; 61:387–92.
46. van Duijnhoven HJR, Roelofs JMB, den Boer JJ, et al. Perturbation-based balance training to improve step quality in the chronic phase after stroke: a proof-of-concept study. *Front. Neurol.* 2018; 9:980.
47. Gerards MHG, McCrum C, Mansfield A, Meijer K. Perturbation-based balance training for falls reduction among older adults: current evidence and implications for clinical practice. *Geriatr. Gerontol. Int.* 2017; 17(12):2294–303.
48. Okubo Y, Sturnieks DL, Brodie MA, Duran L, Lord SR. Effect of reactive balance training involving repeated slips and trips on balance recovery among older adults: a blinded randomized controlled trial. *J. Gerontol A. Biol. Sci. Med. Sci.* 2019; 74:1489–96.
49. Wang Y, Wang S, Lee A, Pai YC, Bhatt T. Treadmill-gait slip training in community-dwelling older adults: mechanisms of immediate adaptation for a progressive ascending-mixed-intensity protocol. *Exp. Brain Res.* 2019; 237:2305–17.
50. Pai YC, Bhatt T, Yang F, Wang E. Perturbation training can reduce community-dwelling older adults' annual fall risk: a randomized controlled trial. *J. Gerontol A. Biol. Sci. Med. Sci.* 2014; 69(12):1586–94.