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RESEARCH ARTICLE

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Effects of tripping conditions and repetitions on reactive balance control during walking and carrying tasks

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ABSTRACT

Falls caused by tripping during walking and load-carrying tasks remain a major source of occupational injury. This study examined the effects of tripping condition, task, and repetition on reactive balance responses. Twenty adults performed walking and carrying tasks under obstacle and cord tripping conditions across six repeated trials. Obstacle tripping produced longer recovery step times and greater recovery step lengths than cord tripping, indicating greater balance recovery demands. Carrying a 6.8-kg anterior load did not greatly impair reactive balance, although it modified repetition-related changes in recovery step length. Repeated exposure was associated with reduced recovery step length during carrying obstacle tripping and reduced trunk flexion during obstacle tripping under both walking and carrying conditions. Perceived recovery difficulty was greater during obstacle tripping, whereas perceived worry decreased across repetitions during walking. These findings indicate that reactive balance responses were mostly affected by perturbation types, while load carriage may influence repetition-related recovery stepping.

PRACTITIONER SUMMARY: Obstacle-like trips created greater balance recovery demands than cord-like trips, leading to longer step times, larger recovery steps and higher perceived recovery difficulty. While carrying a moderate anterior load did not substantially impair initial balance recovery in young adults, it significantly influenced how recovery stepping adapted with repetition. Therefore, occupational fall-prevention simulation and training may utilise mechanically challenging, obstacle-like perturbations that accurately reflect task-specific workplace hazards.

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KEYWORDS
Tripping perturbation; load carriage; balance recovery; fall prevention

Introduction

Falls remain a leading cause of occupational injuries and fatalities in the United States, posing a persistent threat to worker safety and productivity. In 2020, falls accounted for 35.3% of all construction-related deaths, while 21,400 nonfatal injuries and illnesses resulted from slips, trips and falls in construction and extraction industries (Helmick and Petosa 2022). Although falls to a lower level cause the majority of fatal incidents, same-level falls constitute approximately 17% of fatal and over 80% of nonfatal occupational injuries (Yeoh, Lockhart, and Wu 2013). Same-level falls frequently arise from tripping during walking or load-carrying tasks in environments with irregular surfaces, cluttered walkways, or limited visibility (Chang et al. 2016; U.S. Bureau of Labor Statistics 2021). Given the high incidence of occupational falls, understanding the biomechanical mechanisms underlying balance loss is essential for developing targeted fall prevention strategies.

During locomotion, reactive balance control enables individuals to restore stability after an unexpected perturbation through coordinated movements that reposition the body's centre of mass (COM) relative to the base of support (Hof, Gazendam, and Sinke 2005; Meyer and Ayalon 2006). A trip occurs when an external perturbation stops the forward motion of the swing limb while the COM continues its forward momentum, demanding a rapid compensatory recovery step and trunk extension to minimise forward rotation (Pavol et al. 2001). The success of recovery depends on both mechanical and neuromuscular factors, including recovery step timing and length, trunk flexion angle and angular velocity (Grabiner and

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Kaufman 2021). Previous studies have identified two recovery strategies following tripping perturbations, described as lowering and elevating strategies. In a lowering strategy, the swing foot is rapidly placed on the ground before the other foot clears the obstacle, whereas in an elevating strategy, the swing foot is lifted and moved forward to clear the obstacle (Pavol et al. 2001). Excessive trunk flexion or delayed recovery steps may increase anterior displacement of the COM and reduce the time available for stability restoration, thereby elevating fall risk (Batcir et al. 2020; Honeycutt, Nevisipour, and Grabiner 2016). Laboratory studies have simulated tripping using obstacles, retractable cords and automated triggering devices to examine these mechanisms (Ko, Ryew, and Hyun 2017; Silver, Mokha, and Peacock 2016; Wang et al. 2020), yet the comparative effects of different tripping conditions on reactive balance remain unclear. Understanding how distinct physical constraints, like clearing a rigid obstacle versus stepping down on a cord, can help understand different mechanisms of falls, categorise different levels of fall risk, and develop task-specific training strategies and interventions for fall prevention.

Occupational tasks often require workers to navigate environments where unexpected perturbations may occur during locomotion. Such perturbations can arise from obstacles, uneven surfaces, or limited visibility, increasing the likelihood of tripping events (Chang et al. 2016). In addition, carrying loads may further influence balance recovery by shifting the body's centre of mass anteriorly, restricting arm movement and partially obstructing the lower visual field (Angelini et al. 2018; Jehu et al. 2019; Park et al. 2010). Limited arm movements can hinder angular momentum regulation during recovery, while reduced visual feedback delays obstacle detection and step initiation (Roos et al. 2008). Although these factors are recognised as contributors to occupational fall risk, the effects of different tripping conditions and load-carrying tasks on reactive balance control have not been examined. In addition, repeated exposure to perturbations may induce adaptive improvements in postural responses, informed by principles of error-based motor learning. Evidence from perturbation-based balance training suggests that sensory prediction errors generated during early perturbation trials may facilitate adaptation of reactive stepping responses (Bhatt, Yang, and Pai 2012). Such adaptation may involve a transition from an initial generalised response towards more task-specific reactive strategies that improve balance stability (Bierbaum, Peper, and Arampatzis 2013; McCrum et al. 2022; Wang et al. 2020). However, whether similar adaptive responses occur during more complex occupational tasks, such as carrying under different types of tripping mechanisms, remains unclear.

The present study aimed to quantify the effects of tripping conditions (obstacle vs. cord) and tasks (walking vs. carrying) on reactive balance control and to examine potential adaptation in reactive balance control across repeated tripping trials (first vs. sixth trials). Due to the constraint of the cord on the motion of the foot and the external load, it was hypothesised that cord tripping and carrying would induce longer recovery step times, larger step lengths and greater trunk flexion angles compared with obstacle tripping and walking, respectively. Additionally, it was hypothesised that participants would demonstrate improved reactive balance mechanics across repeated exposures, characterised by shorter recovery step times, step lengths and smaller trunk flexion angles in the sixth trial compared to the first trial. This design was needed to determine whether reactive balance responses and short-term adaptations reflect a general response to tripping or depend on the specific mechanical constraints imposed by obstacle and cord perturbations during walking and carrying tasks. These findings may enhance the understanding of different tripping-induced fall mechanisms and reactive balance adaptations under repetitive perturbations, which might support the development of interventions incorporating multiple tripping scenarios to improve task-specific reactive balance for fall prevention in the workplace. The findings may also help categorise different levels of fall risk associated with different working environments with increased exposure to obstacles or cords and different occupational tasks, including walking and carrying. A positive repetition effect on balance recovery control would support the potential effectiveness of perturbation training as a strategy for occupational fall prevention.

Methods

Participants

The estimated effect size was based on a prior trip-perturbation training study in which peak trunk angle decreased with a large effect size after repeated obstacle-induced trips (Wang et al. 2020). Using G*Power with an estimated effect size of 1.0, $\alpha = 0.05$, and power = 0.80 for a paired comparison, a minimum sample size of 10 participants was required. Twenty healthy adults were recruited to exceed the minimum required sample size with similar numbers of male and female participants. The final sample included 11 males and 9 females (age = 22.9 ± 4.1 years; height = 1.70 ± 0.08 m; mass = 71.1 ± 12.4 kg; body mass index [BMI] = 24.66 ± 3.18 kg·m^{-2}) who participated in this study. Participants were required to have a minimum of 500 working hours (approximately 3 months of full-time or 6 months of half-time employment) in occupations characterised by elevated risk of falls and manual material handling tasks such as transportation and warehousing, manufacturing, healthcare, accommodation and food service and construction (Yeoh, Lockhart, and Wu 2013). The time frame during which the participants undertook the occupations was not controlled. Individuals were excluded from the study if they: (1) were using an assistive device to ambulate; (2) had osteoporosis or a fragility fracture; (3) had been hospitalised in the last year; (4) had orthopaedic surgeries to the spine or lower extremities in the last five years; (5) had an acute spinal or lower extremity injury that restricted physical activities for more than one week in the last six months; (6) had a concussion in the last 12 months or have had more than one concussion in their lifetime; (7) had any cardiovascular, pulmonary, or musculoskeletal problems, neurological disorders, uncorrected hearing and vision limitations, or balance challenges that limit daily activities or communication; (8) were allergic to latex or adhesive; or (9) were or might be pregnant. All questions related to the exclusion criteria were self-reported. This study was approved by the University of Wyoming Institutional Review Board. Written informed consent was obtained from each participant before participation.

Procedures

After providing consent, participants' height and body mass were measured, followed by a standardised warm-up consisting of a five-minute walk/jog and dynamic stretching (walking high kicks, walking quadriceps stretch, lunges and lateral shuffles). Participants wore modified safety glasses in which the lower half of the lenses was covered to occlude the lower visual field and reduce their ability to see the obstacle, cord, or perturbation timing (Silver, Mokha, and Peacock 2016). Participants also listened to construction noise through wireless earphones to minimise auditory anticipation of the perturbation and better simulate occupational environments. A full-body marker set was used to define body segments and calculate gait events, approaching speed, recovery step length and trunk flexion angles (Figure 1). A ceiling-mounted safety harness system was used to prevent participants' knees from contacting the ground in the event of a loss of balance. Each participant completed familiarisation trials consisting of four walking and four carrying trials without tripping to become accustomed to the walkway and apparatus. Subsequently, participants performed walking and carrying tasks along a 15-m walkway under four randomised tripping conditions: (1) walking with obstacle tripping, (2) walking with

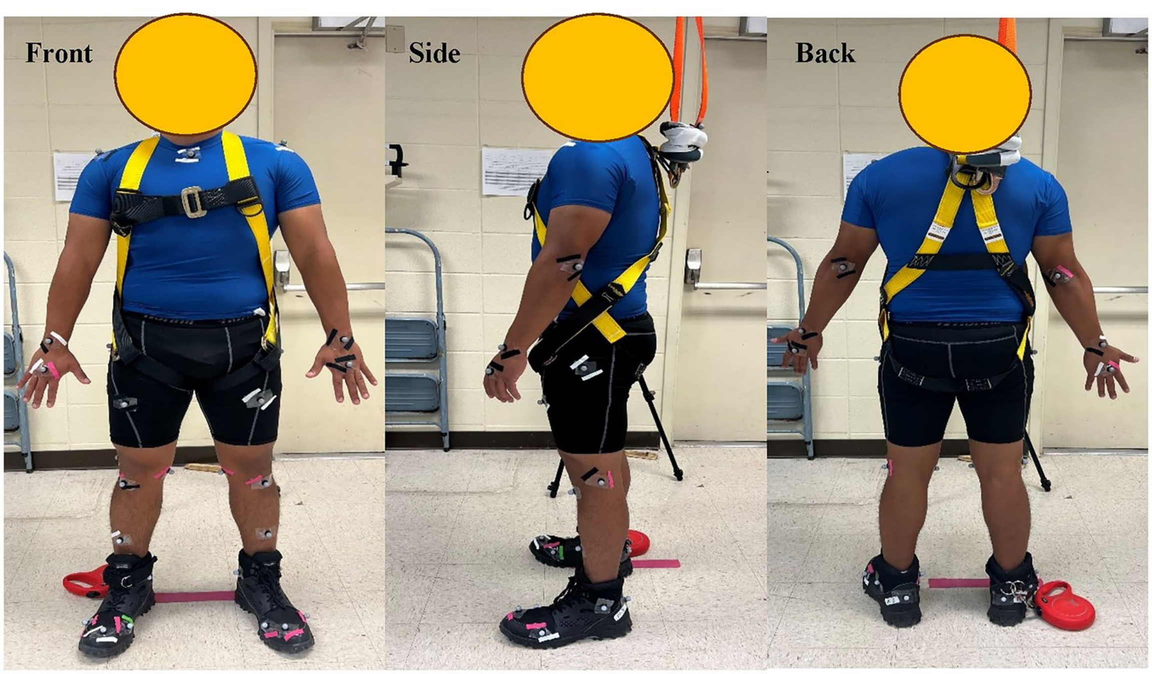

Figure 1. Frontal, side and back views of a participant wearing reflective markers.

cord tripping, (3) carrying with obstacle tripping and (4) carrying with cord tripping.

For both walking and carrying tasks, participants were instructed to walk at their preferred speeds. For the carrying trials, participants held a 15-lb (6.8 kg) plastic box with handles positioned anteriorly at mid-torso level with flexed elbows. For the obstacle tripping condition (Figure 2), a 19-cm high brick was manually moved by a researcher to half of the step length in front of the participant's foot so that the foot contacted the obstacle in the middle of the swing phase, similar to a previous study (Ko, Ryew, and Hyun 2017). For the cord-tripping condition (Figure 3), a retractable and non-stretch cord attached around the participant's ankle was stopped manually by a researcher when the foot was in the middle of the swing phase, stopping the forward motion of the foot, similar to a previous pulling and tripping strategy (König et al., 2019).

Each participant completed six blocks of the four conditions for a total of 24 tripping trials. Within each block, trials of the four experimental conditions were randomised to ensure a balance among different conditions being tested at the beginning and at the end of the data collection. 30-second rest periods were provided between trials to reduce fatigue. Any repeated trials were moved to the end of a block to reduce predictability. The tripped leg (left or right) was counterbalanced across participants, with approximately half experiencing tripping on the left leg and half on the right leg, to control for potential effects of limb dominance on recovery responses. To further reduce anticipation, zero to two trials without tripping were randomly inserted between consecutive tripping trials. In these trials, participants walked along the walkway without any perturbation, limiting participants' ability to predict when a tripping trial would occur. After each perturbation, participants rated their perceived worry ('How worried were you when walking on this walkway?') and perceived difficulty of balance recovery ('How difficult was the last trial for you to recover your balance and avoid falls?') using a five-point Likert scale ranging from 1 ('not at all' / 'easy') to 5 ('extremely' / 'too hard'). The rating was obtained retrospectively to avoid influencing participants' anticipation of the type of perturbation during the trials.

Reflective markers were placed bilaterally on the acromioclavicular joints, elbows, wrists, greater trochanters, anterior thighs, medial and lateral femoral condyles, tibial tuberosities, inferior tibias, medial and lateral malleoli, heels, first and fifth metatarsal heads and toes. Additional markers were attached to the load-carrying box and safety harness cord to confirm

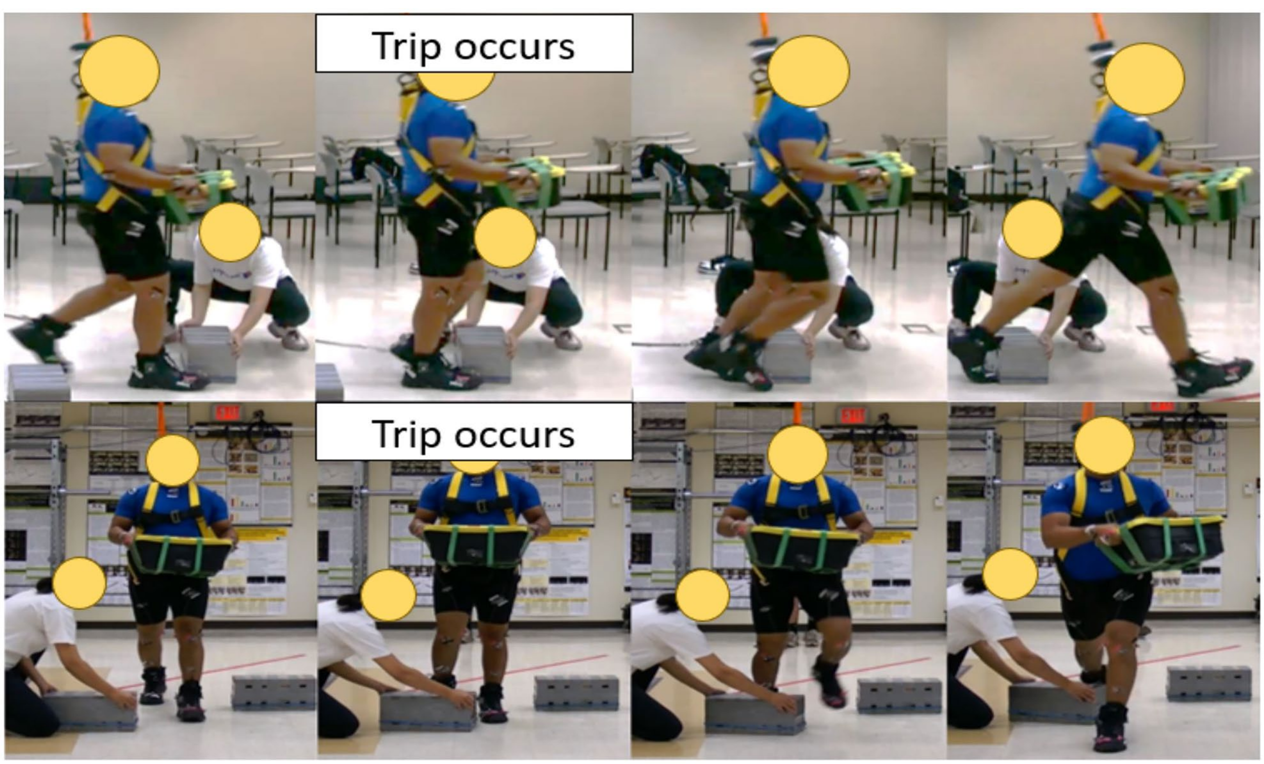

Figure 2. Side and frontal views of carrying a load with the obstacle tripping. A lowering recovery stepping strategy was used in this case.

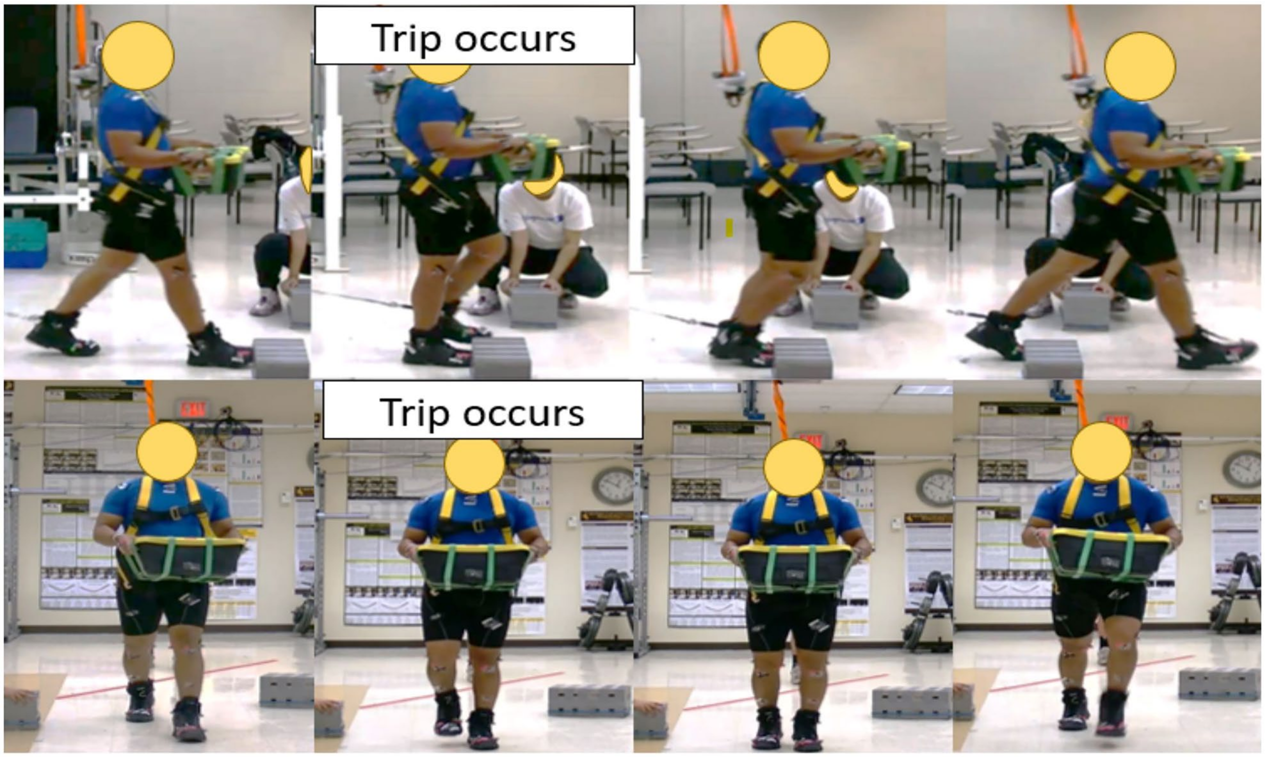

Figure 3. Side and frontal views of carrying a load with the cord tripping. A lowering recovery stepping strategy was used in this case.

harness engagement in the event of a fall. Kinematic data were captured by eight Bonita cameras (Vicon, Oxford, UK) at 160 Hz. A camcorder was used to record sagittal-plane motion to verify possible fall events. A fall was defined as an event requiring support from the harness to prevent ground contact.

Data processing

The first and sixth trials for each participant were used for data analyses. A total of 160 tripping trials were analysed across all participants (20 participants × 4 experimental conditions × 2 trials per condition). Six trials among the 160 trials were excluded from analysis due to missing markers required to calculate the dependent variables: two from the first carrying-obstacle condition, one from the first carrying-cord condition and three from the sixth walking-obstacle condition. Marker gaps were filled using the Cubic Spline Interpolation in Vicon Nexus or the marker position relative to other markers on the same segment. Marker position data were filtered using fourth-order Butterworth filters at 15 Hz. A trial was classified as a fall if the safety harness system engaged to support body weight. A tripping trial was categorised as a lowering strategy in which the tripped foot was lowered and the other leg was used to complete the compensatory step, or an elevating strategy in which the tripped foot was elevated over the obstacle to complete the compensatory step. It should be noted that the cord tripping condition only allowed the lowering strategy, while the obstacle tripping condition allowed both the lowering and the elevating strategies.

Each trial was cut to include multiple frames before the perturbed foot left the ground and multiple frames after the foot of the compensatory stepping leg contacted the ground. The toe-off event was defined as the first frame in which the upward velocity of the toe marker of the tripping leg exceeded 0.1 ms^{-1}. The perturbation event was defined as the first frame in which the posterior acceleration of the toe marker of the tripping leg exceeded 5 ms^{-2}, with this threshold determined through visual comparison between acceleration data and the observed tripping motion to ensure accurate and consistent identification of perturbation onset. The toe-touch event was defined as the first frame in which the downward velocity of the toe marker of the compensatory stepping leg was less than 0.1 ms^{-1} after the marker began to move downward. Perturbation time (s) was calculated as the time interval between toe-off and the perturbation event, and step time (s) was calculated as the time interval between the perturbation and toe-touch events. Approaching speed (ms^{-1}) was calculated as the average forward velocity of the centre of hip markers between toe-off and perturbation events. Recovery step length (m) was measured as the horizontal distance between the toe markers of the stance leg at perturbation and the compensatory stepping leg at toe-touch. The stance leg was the tripping leg when a lowering strategy was used, and the stance leg was the non-tripping leg when an elevating strategy was used. Trunk flexion angle (°) was calculated as the sagittal plane angle formed by the line connecting the acromion and greater trochanter relative to the vertical axis, extracted at both toe-touch and the maximal value within 100 ms after toe-touch. The 100 ms window was selected based on prior studies demonstrating that trip-induced responses, including peak trunk flexion angle, typically occurred within 100 ms following perturbation onset (Sessoms et al. 2014; Shih, Gregor, and Lee 2023).

Statistical analysis

Means and standard deviations were calculated for each tripping condition, task and repetition condition. Due to missing marker data in six trials, repeated-measures ANOVA was conducted using complete cases, resulting in a final sample size of 15 participants. A three-way repeated-measures ANOVA was performed to examine the effects of tripping condition (obstacle vs. cord), task (walking vs. carrying) and repetition (first vs. sixth trial), including all interaction terms. To address the significant three-way and two-way interactions, a simple main effects analysis was conducted using pairwise comparisons with Bonferroni adjustments to control for Type I error inflation. Partial eta squared (η^2p) was reported as a measure of effect size. Subjective responses (Perceived Worry and Recovery Difficulty) were summarised using median and interquartile range (IQR), and Wilcoxon signed-rank tests were used to compare perceived worry and recovery difficulty across conditions. Dependent variables included approaching speed, perturbation time, step time, step length, trunk flexion at touchdown, peak trunk flexion angles and perceived worry and recovery difficulty scores. All statistical analyses were performed using SPSS version 29 (IBM Corp., Armonk, NY). The significance level was set at $\alpha = 0.05$.

Results

None of the trials resulted in an actual fall that engaged the harness.

Approaching speed and perturbation timing

A significant tripping condition × task × repetition interaction was observed for approaching speed ($p = 0.014$, $\eta^2p = 0.358$; Appendix 1). Pairwise comparisons indicated that during the first trial of the walking task, approaching speed was significantly higher for the obstacle than for the cord (Table 1). Additionally, for the cord tripping condition, approaching speed was lower during walking than carrying in the first trial and increased from the first to the sixth walking trial. No other significant pairwise differences were observed for approaching speed. No significant main or interaction effects were observed for perturbation time.

Recovery step responses

A significant main effect of tripping condition was observed for recovery step time ($p < 0.001$, $\eta^2p = 0.766$, Appendix 1). Obstacle tripping produced a longer recovery step time than cord tripping across all task and repetition conditions (Table 1). For recovery

Table 1. Means ± SD of repeated measures ANOVA for the two tripping conditions, the two movement tasks, and the repetition (first and sixth trials).

	Tripping condition	Walking task		Carrying task	
		First trial	Sixth trial	First trial	Sixth trial
Approaching speed (m/s)	Obstacle	1.15 ± 0.21*	1.14 ± 0.22	1.12 ± 0.21	1.16 ± 0.20
	Cord	1.07 ± 0.18#^*	1.17 ± 0.22#	1.14 ± 0.17^	1.15 ± 0.21
Perturbation time (s)	Obstacle	0.19 ± 0.04	0.27 ± 0.28	0.17 ± 0.04	0.21 ± 0.03
	Cord	0.16 ± 0.03	0.19 ± 0.03	0.17 ± 0.03	0.17 ± 0.02
Recovery step time (s)	Obstacle	0.62 ± 0.09*	0.66 ± 0.18*	0.65 ± 0.06*	0.60 ± 0.06*
	Cord	0.51 ± 0.10*	0.52 ± 0.09*	0.53 ± 0.10*	0.51 ± 0.10*
Recovery step length (m)	Obstacle	1.05 ± 0.25*^	1.05 ± 0.20*	1.17 ± 0.22*#^	1.02 ± 0.16*#
	Cord	0.87 ± 0.20*^	0.90 ± 0.14*	0.92 ± 0.18*^	0.89 ± 0.13*
Trunk flexion angle at touchdown (°)	Obstacle	18.75 ± 9.80#	13.82 ± 10.74#	18.75 ± 12.07#	13.12 ± 8.66#
	Cord	15.86 ± 8.44	16.47 ± 8.09	12.13 ± 11.77	12.94 ± 8.59
Peak trunk flexion angle 100 ms after touchdown (°)	Obstacle	22.57 ± 12.11*#	15.04 ± 11.52#	21.67 ± 12.20*#	14.95 ± 10.13#
	Cord	17.60 ± 10.16*	16.82 ± 8.30	14.76 ± 14.25*	13.82 ± 10.03

Note: Significant effects of tripping conditions for each movement task and each trial were indicated by *; significant effects of movement tasks for each tripping condition and each trial were indicated by ^; significant effects of the two trials for each tripping condition and each movement tasks were indicated by #.

Table 2. Results of Wilcoxon signed-rank tests (median and IQR) for survey responses across condition, task and repetition.

	Tripping condition	Walking task		Carrying task	
		First trial	Sixth trial	First trial	Sixth trial
Perceived worry response (point)	Obstacle	2.00 (2.00, 3.00)#	1.00 (1.00, 2.00)#	2.00 (2.00, 3.00)	1.00 (1.00, 2.00)
	Cord	2.00 (2.00, 3.00)#	1.00 (1.00, 2.00)#	2.00 (2.00, 3.00)	1.00 (1.00, 2.00)
Recovery difficulty response (point)	Obstacle	2.00 (2.00, 3.00)*#	2.00 (1.00, 2.00)#	2.00 (1.00, 3.00)*	2.00 (2.00, 3.00)*
	Cord	2.00 (1.00, 2.00)*	1.00 (1.00, 2.00)	1.00 (1.00, 2.00)*	1.00 (1.00, 2.00)*

Note: Values are presented as median with interquartile range in parentheses. Significant effects of tripping conditions for each movement task and each trial were indicated by *; significant effects of the two trials for each tripping condition and each movement tasks were indicated by #.

step length, significant tripping condition × repetition ($p = 0.047$, $\eta^2p = 0.253$) and task × repetition ($p = 0.015$, $\eta^2p = 0.352$) interactions were observed. Pairwise comparisons showed that obstacle tripping produced greater recovery step length than cord tripping across all task and repetition conditions. During the first trial, carrying resulted in greater recovery step length than walking for both obstacle and cord tripping. Recovery step length decreased from the first to the sixth trial during carrying obstacle tripping.

Trunk flexion responses

Significant tripping condition × repetition interactions were observed for trunk flexion angle at touchdown ($p = 0.028$, $\eta^2p = 0.300$) and peak trunk flexion angle 100 ms after touchdown ($p = 0.033$, $\eta^2p = 0.285$, Appendix 1). Pairwise comparisons showed that both trunk flexion angle at touchdown and peak trunk flexion angle decreased from the first to the sixth trial during obstacle tripping under both walking and carrying conditions (Table 1). In addition, peak trunk flexion angle was greater during obstacle tripping than cord tripping during the first walking and carrying trials.

Subjective responses

For perceived worry responses, significant reductions from the first to the sixth trial were observed during both walking conditions for obstacle and cord tripping (Table 2). For recovery difficulty responses, obstacle tripping resulted in greater perceived difficulty than cord tripping across most tasks and repetition conditions. Recovery difficulty responses also decreased from the first to the sixth trial during obstacle walking trials.

Discussion

The purpose of this study was to examine the effects of tripping conditions, task demands and repeated exposure on reactive balance control. We hypothesised that the cord-tripping condition and carrying task would show increased recovery step time and step lengths and greater trunk flexion angles when compared to the obstacle-tripping condition and walking task. We also hypothesised that participants would demonstrate shorter recovery step times, step lengths and smaller trunk flexion angles in the sixth trial compared to the first trial.

The results did not support the hypothesis related to the comparison between cord tripping and obstacle tripping. Cord tripping resulted in shorter recovery step time and shorter recovery step length, indicating a smaller perturbation that allowed participants to restore stability with faster and smaller corrective steps. These differences were observed consistently across walking and carrying tasks and across repetitions, indicating that the two tripping conditions imposed different mechanical demands on reactive balance recovery. During obstacle tripping, contact with a rigid obstacle abruptly halted the swing limb while the body's COM continued forward. Such a sudden perturbation likely requires greater recovery step adjustments to reposition the COM within the base of support (Grabiner and Kaufman 2021; Pavol, Runtz, and Pai 2004). Although approaching speed showed a significant tripping condition × task × repetition interaction, pairwise differences were limited to the first walking trial and therefore do not fully explain the consistent differences in recovery step time and step length between tripping conditions. This interpretation is supported by the observed distribution of recovery strategies. Obstacle tripping allowed both elevating and lowering responses, whereas cord tripping was limited to lowering strategies. In a lowering strategy, the tripped foot is rapidly placed on the ground, and the opposite limb completes the compensatory step; in an elevating strategy, the tripped foot is lifted over the obstacle to complete the compensatory step. While all recovery steps in the cord condition utilised a lowering strategy, a portion (13%) of obstacle tripping trials were resolved using an elevating strategy, agreeing with previous work showing that obstacle-like perturbations preferentially elicit elevating responses while less severe perturbations allow for lowering (Eng, Winter, and Patla 1994; Schillings, Mulder, and Duysens 2005). Furthermore, even when the lowering strategy was used for both hazards, the obstacle likely constrained the placement of the tripping foot, requiring it to move back slightly to minimise friction and clear the object. In contrast, the cord allowed the foot to be placed directly down quickly without any vertical constraint. Thus, biomechanically speaking, the obstacle-tripping mechanism imposed a greater physical constraint that necessitated more expansive recovery movements. Importantly, these mechanical constraints were directly reflected in the participants' subjective experiences; recovery difficulty ratings were significantly higher during obstacle tripping compared to cord tripping across nearly all conditions, confirming that the physical demands of the rigid obstacle translated into a higher perceived threat to balance.

Perturbation time did not show significant main or interaction effects, indicating that the timing of perturbation onset was generally comparable across tripping condition, task and repetition. Therefore, the consistent differences in recovery step time and recovery step length between obstacle and cord tripping were unlikely to be primarily explained by systematic differences in perturbation timing. Instead, these findings further support the interpretation that the mechanical characteristics of the perturbation, particularly the rigid physical constraint imposed by the obstacle, played a dominant role in shaping reactive stepping responses.

The hypothesis regarding the comparison between the walking and carrying tasks was partially supported. The carrying task did not produce consistent increases in recovery step time or trunk flexion compared with walking, indicating that the 6.8-kg anterior load did not broadly impair reactive balance recovery in this young adult sample. However, recovery step length exhibited a significant Task × Repetition interaction. During the first trial, carrying resulted in a significantly greater recovery step length than walking for both the obstacle and cord conditions, whereas this task-related difference was no longer present by the sixth trial. This pattern suggests that while carrying a load initially increased the spatial demand of the recovery response, this effect was rapidly reduced after repeated exposure. This finding differs from previous occupational studies reporting increased fall risk or altered obstacle negotiation during load handling (Angelini et al. 2018; Park et al. 2010; Perry et al. 2010). Important experimental differences likely account for this discrepancy. Prior studies often examined posterior or asymmetric loads, which can increase postural sway and shift the COM rearward or laterally, or they included older and heavier participants (Perry et al. 2010). In the present study, participants carried a 6.8-kg anterior load, representing approximately 10% of their body mass. Although loads of this magnitude may shift the COM anteriorly and influence static postural control (Roberts et al. 2018; Shigaki et al. 2017), these kinematic changes did not translate into persistent impairment during dynamic reactive balance recovery. Ultimately, for young, healthy adults, an anterior load of this magnitude appears to remain within a manageable threshold that can be successfully compensated for through anticipatory postural adjustments (Li and Aruin 2007).

The hypothesis regarding balance improvements across repeated exposures was partially supported. Repetition-related changes were most evident in recovery step length and trunk flexion responses, and these changes depended on the task and tripping condition. Recovery step length decreased from the first to the sixth trial, specifically during carrying obstacle tripping, while trunk flexion angle at touchdown and peak trunk flexion angle decreased across trials during obstacle tripping under both walking and carrying conditions. These findings are generally consistent with previous studies showing that repeated perturbation exposure can improve reactive balance responses and reduce trunk motion during trip recovery (Bierbaum, Peper, and Arampatzis 2013; Wang et al. 2020). The reduction in trunk flexion during obstacle tripping may indicate improved control of forward body rotation after repeated exposure (Bieryla, Madigan, and Nussbaum 2007; Rosenblatt, Marone, and Grabiner 2013).

In contrast, cord tripping showed relatively stable recovery steps and trunk flexion responses across repetitions, suggesting that this perturbation imposed a smaller mechanical challenge and provided less stimulus for measurable short-term biomechanical adaptation. Prior perturbation-based balance training studies indicate that adaptive kinematic improvements are more likely when perturbations are sufficiently destabilising to genuinely challenge the balance control system (Allin et al. 2020; Guadagnoli & Lee 2004; McCrum et al. 2022). Therefore, the present findings suggest that short-term biomechanical adaptation occurred primarily under the more mechanically demanding obstacle-tripping condition.

Subjective responses provided crucial context for interpreting these biomechanical adaptations. Recovery difficulty ratings were consistently higher during obstacle tripping than cord tripping across most task and repetition conditions, aligning directly with the longer recovery step times and greater step lengths observed during obstacle tripping. Furthermore, perceived worry decreased from the first to the sixth trial during walking for both obstacle and cord tripping, suggesting that repeated exposure successfully reduced perceived threat during unburdened gait (Johnson et al. 2019). However, this psychological habituation was not observed during the carrying tasks, indicating that carrying a load maintained a high level of perceived challenge even when objective task-related kinematic changes were limited. Together, these findings demonstrate a distinct divergence in psychological response: perceived recovery difficulty was primarily dictated by perturbation severity, whereas perceived worry was distinctly sensitive to the interaction between repeated exposure and the physical constraints of load carriage.

Several limitations must be considered. First, participants were aware that a trip could occur to a predetermined leg, which may have elicited anticipatory gait adjustments. Second, although perturbation time did not differ significantly across conditions, achieving consistent perturbation timing across individuals was challenging due to natural variability during overground walking and the manual perturbation methods used in the current study, which may have increased variability in the recovery responses. Third, participants were young, healthy adults who met restrictive exclusion criteria, and the mean BMI was close to the overweight threshold. Therefore, the findings may not generalise to older workers, individuals with obesity, clinical populations, or workers with balance-related limitations. Fourth, the researchers originally planned to include the whole-body centre of mass, but the markers on the arms and boxes were commonly blocked due to the presence of the box, limiting direct assessment of dynamic stability. Future studies with other motion capture methods or better marker sets and camera configurations may address this challenge. Finally, the participants performed six trials in a row, while the long-term learning and retention effects of the repetition on reactive balance after tripping were unknown.

In summary, obstacle tripping imposed greater reactive balance demands than cord tripping, as demonstrated by longer recovery step time and greater recovery step length across task and repetition conditions. Carrying a moderate anterior load did not broadly impair reactive balance responses in healthy young adults, although it modified repetition-related changes in recovery step length. Repeated exposure led to condition-specific changes in balance recovery, with reduced recovery step length during carrying obstacle tripping and reduced trunk flexion responses during obstacle tripping under both walking and carrying conditions. These physical adaptations were directly mirrored by participants' subjective perceptions of difficulty and worry. These findings indicate that perturbation characteristics play a primary role in shaping reactive balance responses, while load carriage may influence how recovery stepping changes across repeated exposures. The results support the use of mechanically challenging, obstacle-like perturbations when examining reactive balance control and developing occupational fall-prevention strategies.

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Disclosure statement

None.

Ethical approval statement

The study was approved by the Institutional Review Board of the University of Wyoming (Approval #20230706BD03601). Written informed consent was obtained from all participants prior to participation.

Use of generative artificial intelligence

Generative AI tools were used to refine the language and improve the clarity of this manuscript. Specifically, ChatGPT (GPT-5.2, OpenAI) was employed to assist with wording adjustments and conciseness in the main text. The authors reviewed, edited and approved all AI-assisted content and take full responsibility for the integrity and accuracy of the manuscript.

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References

Allin, L. J., P. G. Brolinson, B. M. Beach, S. Kim, M. A. Nussbaum, K. A. Roberto, and M. L. Madigan. 2020. "Perturbation-Based Balance Training Targeting Both Slip- and Trip-Induced

Falls among Older Adults: A Randomized Controlled Trial." *BMC Geriatrics* 20 (1): 205. doi:10.1186/s12877-020-01605-9.

Angelini, M. J., R. M. Kesler, M. N. Petrucci, K. S. Rosengren, G. P. Horn, and E. T. Hsiao-Wecksler. 2018. "Effects of Simulated Firefighting and Asymmetric Load Carriage on Firefighter Obstacle Crossing Performance." *Applied Ergonomics* 70: 59–67. doi:10.1016/j.apergo.2018.02.006.

Batcir, S., G. Shani, A. Shapiro, N. Alexander, and I. Melzer. 2020. "The Kinematics and Strategies of Recovery Steps during Lateral Losses of Balance in Standing at Different Perturbation Magnitudes in Older Adults with Varying History of Falls." *BMC Geriatrics* 20 (1): 249. doi:10.1186/s12877-020-01650-4.

Bhatt, T., F. Yang, and Y. C. Pai. 2012. "Learning to Resist Gait-Slip Falls: Long-Term Retention in Community-Dwelling Older Adults." *Archives of Physical Medicine and Rehabilitation* 93 (4): 557–564. doi:10.1016/j.apmr.2011.10.027.

Bierbaum, S., A. Peper, and A. Arampatzis. 2013. "Exercise of Mechanisms of Dynamic Stability Improves the Stability State after an Unexpected Gait Perturbation in Elderly." *Age (Dordrecht, Netherlands)* 35 (5): 1905–1915. doi:10.1007/s11357-012-9481-z.

Bieryla, K. A., M. L. Madigan, and M. A. Nussbaum. 2007. "Practicing Recovery from a Simulated Trip Improves Recovery Kinematics after an Actual Trip." *Gait & Posture* 26 (2): 208–213. doi:10.1016/j.gaitpost.2006.09.010.

Chang, W. R., S. Leclercq, T. E. Lockhart, and R. Haslam. 2016. "State of Science: Occupational Slips, Trips and Falls on the Same Level." *Ergonomics* 59 (7): 861–883. doi:10.1080/00140139.2016.1157214.

Eng, J. J., D. A. Winter, and A. E. Patla. 1994. "Strategies for Recovery from a Trip in Early and Late Swing during Human Walking." *Experimental Brain Research* 102 (2): 339–349. doi:10.1007/BF00227520.

Grabiner, M. D., and K. R. Kaufman. 2021. "Developing and Establishing Biomechanical Variables as Risk Biomarkers for Preventable Gait-Related Falls and Assessment of Intervention Effectiveness." *Frontiers in Sports and Active Living* 3: 722363. doi:10.3389/fspor.2021.722363.

Guadagnoli, M. A., and T. D. Lee. 2004. "Challenge Point: A Framework for Conceptualizing the Effects of Various Practice Conditions in Motor Learning." *Journal of Motor Behavior* 36 (2): 212–224. doi:10.3200/JMBR.36.2.212-224.

Helmick, N., and J. Petosa. 2022. Workplace injuries and job requirements for construction laborers. *U.S. Bureau of Labor Statistics*. https://www.bls.gov/spotlight/2022/workplace-injuries-and-job-requirements-for-construction-laborers/home.htm

Hof, A. L., M. G. J. Gazendam, and W. E. Sinke. 2005. "The Condition for Dynamic Stability." *Journal of Biomechanics* 38 (1): 1–8. doi:10.1016/j.jbiomech.2004.03.025.

Honeycutt, C. F., M. Nevisipour, and M. D. Grabiner. 2016. "Characteristics and Adaptive Strategies Linked with Falls in Stroke Survivors from Analysis of Laboratory-Induced Falls." *Journal of Biomechanics* 49 (14): 3313–3319. doi:10.1016/j.jbiomech.2016.08.019.

Jehu, D. A., D. Saunders, N. Richer, N. Paquet, and Y. Lajoie. 2019. "The Influence of Carrying an Anterior Load on Attention Demand and Obstacle Clearance before, during, and after Obstacle Crossing." *Experimental Brain Research* 237 (12): 3313–3319. doi:10.1007/s00221-019-05673-1.

Johnson, K. J., M. Zaback, C. D. Tokuno, M. G. Carpenter, and A. L. Adkin. 2019. "Repeated Exposure to the Threat of Perturbation Induces Emotional, Cognitive, and Postural Adaptations in Young and Older Adults." *Experimental Gerontology* 122: 109–115. doi:10.1016/j.exger.2019.04.015.

Ko, Y., C. Ryew, and S. Hyun. 2017. "Relationship among the Variables of Kinematic and Tilt Angle of Whole Body according to the Foot Trip during Gait." *Journal of Exercise Rehabilitation* 13 (1): 117–121. doi:10.12965/jer.1732846.423.

König, M., G. Epro, J. Seeley, P. Catalá-Lehnen, W. Potthast, and K. Karamanidis. 2019. "Retention of Improvement in Gait Stability over 14 Weeks Due to Trip-Perturbation Training is Dependent on Perturbation Dose." *Journal of Biomechanics* 84: 243–246. doi:10.1016/j.jbiomech.2018.12.011.

Li, X., and A. S. Aruin. 2007. "The Effect of Short-Term Changes in the Body Mass on Anticipatory Postural Adjustments." *Experimental Brain Research* 181 (2): 333–346. doi:10.1007/s00221-007-0931-2.

McCrum, C., T. Bhatt, M. Gerards, K. Karamanidis, M. Rogers, S. Lord, and Y. Okubo. 2022. "Perturbation-Based Balance Training: Principles, Mechanisms and Implementation in Clinical Practice." *Frontiers in Sports and Active Living* 4: 1015394. doi:10.3389/fspor.2022.1015394.

Meyer, G., and M. Ayalon. 2006. "Biomechanical Aspects of Dynamic Stability." *European Review of Aging and Physical Activity* 3 (1): 29–33. doi:10.1007/s11556-006-0006-6.

Park, K., P. Hur, K. S. Rosengren, G. P. Horn, and E. T. Hsiao-Wecksler. 2010. "Effect of Load Carriage on Gait Due to Firefighting Air Bottle Configuration." *Ergonomics* 53 (7): 882–891. doi:10.1080/00140139.2010.489962.

Pavol, M. J., T. M. Owings, K. T. Foley, and M. D. Grabiner. 2001. "Mechanisms Leading to a Fall from an Induced Trip in Healthy Older Adults." *The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences* 56 (7): M428–M437. doi:10.1093/gerona/56.7.M428.

Pavol, M. J., E. F. Runtz, and Y. C. Pai. 2004. "Diminished Stepping Responses Lead to a Fall following a Novel Slip Induced during a Sit-to-Stand." *Gait & Posture* 20 (2): 154–162. doi:10.1016/j.gaitpost.2003.08.004.

Perry, C. J., J. B. Kiriella, K. M. Hawkins, C. J. Shanahan, A. E. Moore, and W. H. Gage. 2010. "The Effects of Anterior Load Carriage on Lower Limb Gait Parameters during Obstacle Clearance." *Gait & Posture* 32 (1): 57–61. doi:10.1016/j.gaitpost.2010.03.003.

Roberts, M., C. Talbot, A. Kay, M. Price, and M. Hill. 2018. "Changes in Postural Sway and Gait Characteristics as a Consequence of Anterior Load Carriage." *Gait & Posture* 66: 139–145. doi:10.1016/j.gaitpost.2018.08.039.

Roos, P. E., M. P. McGuigan, D. G. Kerwin, and G. Trewartha. 2008. "The Role of Arm Movement in Early Trip Recovery in Younger and Older Adults." *Gait & Posture* 27 (2): 352–356. doi:10.1016/j.gaitpost.2007.05.001.

Rosenblatt, N. J., J. Marone, and M. D. Grabiner. 2013. "Preventing Trip-Related Falls by Community-Dwelling Adults: A Prospective Study." *Journal of the American Geriatrics Society* 61 (9): 1629–1631. doi:10.1111/jgs.12428.

Schillings, A. M., T. Mulder, and J. Duysens. 2005. "Stumbling over Obstacles in Older Adults Compared to Young Adults." *Journal of Neurophysiology* 94 (2): 1158–1168. doi:10.1152/jn.00396.2004.

Sessoms, P. H., M. Wyatt, M. Grabiner, J. D. Collins, T. Kingsbury, N. Thesing, and K. Kaufman. 2014. "Method for Evoking a Trip-like Response Using a Treadmill-Based Perturbation during Locomotion." *Journal of Biomechanics* 47 (1): 277–280. doi:10.1016/j.jbiomech.2013.10.035.

Shigaki, L., E. R. Vieira, A. W. de Oliveira Gil, C. G. A. Araújo, M. Z. Carmargo, L. A. Sturion, M. R. de Oliveira, and R. A. da Silva. 2017. "Effects of Holding an External Load on the Standing Balance of Older and Younger Adults with and without Chronic Low Back Pain." *Journal of Manipulative and Physiological Therapeutics* 40 (4): 284–292. doi:10.1016/j.jmpt.2017.01.007.

Shih, H. T., R. Gregor, and S. P. Lee. 2023. "Description, Reliability and Utility of a Ground-Reaction-Force Triggered Protocol for Precise Delivery of Unilateral Trip-like Perturbations during Gait." *PloS One* 18 (4): e0284384. doi:10.1371/journal.pone.0284384.

Silver, T. A., G. M. Mokha, and C. A. Peacock. 2016. "Exploring Fall Training Adaptations While Walking." *Work* 54 (3): 699–707. doi:10.3233/WOR-162321.

U.S. Bureau of Labor Statistics. 2021. "Fatal and Nonfatal Falls, Slips, and Trips in the Construction Industry." *The Economics Daily*. https://www.bls.gov/opub/ted/2021/fatal-and-nonfatal-falls-slips-and-trips-in-the-construction-industry.htm

Wang, Y., S. Wang, R. Bolton, T. Kaur, and T. Bhatt. 2020. "Effects of Task-Specific Obstacle-Induced Trip-Perturbation Training: Proactive and Reactive Adaptation to Reduce Fall-Risk in Community-Dwelling Older Adults." *Aging Clinical and Experimental Research* 32 (5): 893–905. doi:10.1007/s40520-019-01268-6.

Yeoh, H. T., T. E. Lockhart, and X. Wu. 2013. "Non-Fatal Occupational Falls on the Same Level." *Ergonomics* 56 (2): 153–165. doi:10.1080/00140139.2012.746739.

Appendix 1. Results of three-way repeated-measures ANOVA (η^2p and *p*-values) examining the effects of tripping condition, task and repetition across dependent variables

	Approaching speed (m/s)	Perturbation time (s)	Recovery step time (s)	Recovery step length (m)	Trunk flexion angle at touchdown (°)	Peak trunk flexion angle 100 ms after touchdown (°)
Condition	0.083 (0.279)	0.239 (0.055)	**0.766 (<0.001)**	**0.672 (<0.001)**	0.080 (0.287)	0.159 (0.126)
Task	0.063 (0.347)	0.091 (0.256)	0.001 (0.891)	0.146 (0.144)	0.247 (0.050)	0.228 (0.062)
Repetition	0.117 (0.194)	0.193 (0.089)	0.004 (0.814)	0.188 (0.094)	0.122 (0.184)	**0.263 (0.042)**
Condition × task	0.164 (0.120)	0.063 (0.348)	0.018 (0.625)	0.015 (0.651)	0.161 (0.123)	0.073 (0.311)
Condition × repetition	0.131 (0.168)	0.088 (0.263)	0.000 (0.950)	**0.253 (0.047)**	**0.300 (0.028)**	**0.285 (0.033)**
Task × repetition	0.021 (0.595)	0.052 (0.395)	0.216 (0.069)	**0.352 (0.015)**	0.001 (0.902)	0.002 (0.871)
Condition × task × repetition	**0.358 (0.014)**	0.005 (0.791)	0.112 (0.204)	0.099 (0.235)	0.009 (0.730)	0.007 (0.751)

Note. Values are presented as partial eta squared (η^2p) with *p*-values in parentheses. Bold indicates a significant difference $p < 0.05$.