Optimizing successful balance recovery from unexpected trips and slips

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Abstract
Approximately one in three people over 65 years of age fall each year. The resulting physiological and psychological trauma can lead to physical deconditioning, social isolation and early mortality. Recent research has reported balance recovery can be trained in a single session resulting in dramatic reductions in fall rates. However, most previous research has used repeated exposures to a single hazard in a fixed location and not controlled for reductions in walking speed. It follows, that the biomechanical mechanisms important for reactive balance recovery (in the absence of anticipatory adjustments) are probably not well understood. Here, we investigated the biomechanics of successful reactive balance recovery following the first exposures to unexpected trip and slip hazards in different locations. Ten healthy adults (29.1±5.6 years) completed 32 walks at fixed speed, cadence and step length over a custom 10-meter walkway while being exposed to randomly presented and located slip and trip hazards. Balance recovery kinematics were assessed using a VICON motion analysis system. Repeated exposures to unexpected hazards induced significant reductions ($p\leq0.05$) in anteroposterior (AP) trunk sway following the trips (26.7° to 14.3°; Cohen’s $d$ -1.24) and slips (32.7° to 19.0°; Cohen’s $d$ -0.93). During recovery from unexpected trips, reduced AP trunk sway was strongly correlated with a more posterior centre-of-mass position relative to the stepping foot ($r=0.91$) and a longer step length ($r=-0.71$). During recovery from unexpected slips, reduced AP trunk sway was moderately correlated with slower slipping speed ($r=0.54$) and a less posterior centre-of-mass position relative to the stance (slipping) foot ($r=-0.39$). The biomechanical mechanisms required for the successful reactive balance recovery from trips and slips were different. Future experimental protocols to optimize reactive balance recovery for fall prevention should therefore use progressive exposures to both slip and trip hazards using specialized equipment and determine if similar biomechanical mechanisms are observed in young and elderly people at risk of falls.

Keywords: Slip, Trip, Fall, Recover, React, Perturb, Elderly, Step, Trunk, Sway

1. Introduction
Approximately one in three people over the age of 65 years fall each year (Masud and Morris, 2001). The resulting physiological and psychological trauma can lead to physical deconditioning, social isolation and early mortality (Masud and Morris, 2001). Maintaining an active lifestyle is essential for health and physical fitness (Brodie et al., 2017; Loef and Walach, 2012; Lollgen et al., 2009). However, for some active elderly people of intermediate ability, increased activity may increase the risk of falling, through increased exposure to trip or slip hazards (Brodie et al., 2017; O’Loughlin et al., 1993; Okubo et al., 2015). These “active” fallers may benefit from a more individualized approach that teaches protective reactions or recovery from hazards that can cause balance loss (Brodie et al., 2015; Ito et al., 2016; Mansfield et al., 2015; Okubo et al., 2017).
Recent research has reported reactive stepping and perturbation training can lead to dramatic reductions in fall rates (Mansfield et al., 2015; Okubo et al., 2017). Perturbation training involves repeated exposures to hazards that can cause balance loss. Injuries are prevented by the use of a harness, which allows participants to be exposed to trip and slip hazards in order to improve their recovery stepping and balance control in a safe environment. Rapid improvements in balance recovery after a single session of repeated exposures to both trips and slips have been reported in the laboratory and this may extend to a 50% reduction in falls in the 12 months follow up period (Bhatt et al., 2006; Bierbaum et al., 2011; Cham and Redfern, 2002; Chambers and Cham, 2007; Moyer et al., 2006; Pai et al., 2010; Pai et al., 2014; Wang et al., 2011, 2012).

The biomechanical mechanisms reported for successful reactive balance recovery after tripping include:

1. Sufficient support limb push-off to provide time and clearance for a recovery step (Pijnappels et al., 2004);
2. reduced trunk rotation and a more posterior centre-of-mass (CoM) position (Wang et al., 2012);
3. slower CoM velocity and increased hip height (Wang et al., 2012); and
4. increased recovery step stability (Bierbaum et al., 2011; Wang et al., 2012).

The biomechanical mechanisms for reported reactive balance recovery after slipping include:

1. Reduced slipping distance and slipping velocity (Wang et al., 2011);
2. decreased backward loss of balance (Bhatt et al., 2006; Pai et al., 2010; Wang et al., 2011);
3. increased hip height (Pai et al., 2010; Wang et al., 2011); and
4. increased recovery step stability (Bhatt et al., 2006; Pai et al., 2010; Wang et al., 2011).

These improvements in reactive balance recovery have been reported despite the likely influences due to changes in the approach gait with repeated exposures. Repeated exposures to a trip hazard in a fixed location can invoke large anticipatory (pre-hazard) reductions in walking speed, approach CoM velocity and increased approach toe clearance and stability (Wang et al., 2012). Anticipation of a slip hazard can result in a 16-33% reduction in the required coefficient of friction related to reduced foot loading speed, a shorter approach step and reduced foot angle at heel strike (Cham and Redfern, 2002; Chambers and Cham, 2007). Repeated exposure to a slip hazard can also result in a more forward CoM position, greater knee flexion and increased approach step stability (Bhatt et al., 2006; Wang et al., 2011).

Such reductions in approach step length and gait speed including the anterior shift of CoM position and increased knee flexion are traditionally taught as Japanese Nanba walking (Yamaguchi and Hokkiriigawa, 2009). These gait adaptions are clearly an effective strategy for dealing with laboratory simulated slips when both the type and location of the hazard are known. In daily-life, however, falls may be caused by different types of unexpected hazards. A recent systematic review of repeated perturbation training found that in 80% of the included studies insufficient washout walks were used between repeated exposure to a hazard (Bohm et al., 2015). Changes in the approach walk (slower gait speed, shorter step lengths and anticipatory postural adjustments) reduce the intensity of the perturbation and therefore may have confounded the reported improvements in reactive balance recovery (Bohm et al., 2015). It follows, that the biomechanical mechanisms important for reactive balance recovery (in the absence of anticipatory adjustments) have probably been overstated and may not be well understood.

In this paper, we investigate the biomechanical mechanisms for successful reactive balance recovery following the first exposures to unexpected trip and slip hazards in different locations. Walking speed, cadence and step length were maintained by our custom walkway (that included the use of stepping targets and a metronome) in order to limit the anticipatory (pre-hazard) adjustments by participants.

2. Methods
2.1 Participants
Informed written consent was obtained from participants prior to their participation (NSW Human Ethics HC16227). Ten healthy adults (5 males and 5 females) participated in the experimental protocol. On average, participants were aged 29.1 (5.6 standard deviation) years, were 176.4 (11.2) cm tall and weighed 70.4 (14.8) Kg. The usual gait speed of the participants was 1.37 (0.19) m/s with a cadence of 110.3 (7.6) steps/min and step length of 74.3 (18.6) cm.
2.2 Walkway description for unexpected slips and trips

We built a custom 10-meter walkway that can deliver both unexpected slips and trips in different locations. The hazards were hidden within a series of identical looking wooden decking tiles. The trip hazard was a 14cm high spring loaded tripping board released remotely to contact the swing foot at mid swing phase. The slipping hazard (when unlocked and stepped on) caused the support foot to slide for 70cm along two low friction linear bearings that were hidden beneath the wooden decking. Along the walkway a series of black and white vinyl stepping tiles were placed to ensure maintenance of usual approach gait step lengths and that the hazards were delivered reliably and effectively. A metronome was used to ensure usual cadence and velocity. In the ceiling above the walkway there was a track for the full body harness to prevent participants experiencing fall-related injuries.

2.3 Experimental protocol

Prior to the experiment, usual gait speed, cadence and step length was measured with a 5m electronic walkway (GAITRite® mat, v4.0, 2010 CIR Systems, USA) and used set the metronome cadence and placement of stepping tiles. Participants were then fitted with the harness and conducted practice walks along the walkway until they were comfortable walking to the metronome and could maintain their usual gait pattern (cadence and step length).

At the beginning of the experiment, participants were informed that they “might encounter a hazard at any point along the walkway” and were provided with no other information. The experimental protocol consisted of 3 conditions based on the location of the slip and trip hazards. In each condition participants completed 4 slip trials and 4 trip trials alternating between the hazard types. In condition 1, the hazards were placed on the right (Rht) side of the walkway at a fixed location in the middle of the walkway. In condition 2 the hazards were placed on the left (Lft) side of the walkway at a fixed location in the middle of the walkway. In condition 3, the hazards were placed either on the right or left side of the walkway and in random (Rnd) near, middle and far locations. A total of 24 hazard trails (12 slips and 12 trips) were completed as follows:

- Condition 1: 4 slips alternating with 4 trips delivered to the right leg (labelled 1.Rht to 4.Rht, Fig 2A & 2B).
- Condition 2: 4 slips alternating with 4 trips delivered to the left leg (5.Lft to 8.Lft, Fig 2A & 2B).
- Condition 3: 4 slips alternating with 4 trips delivered in random locations (9.Rnd to 12.Rnd, Fig 2A & 2B).

2.4 Kinematic parameters

An 8-camera Vicon Bonita motion capture system (Vicon Motion Systems Ltd., Oxford, UK) sampling at 100 Hz was used to collect kinematic data for one approach step and three recovery steps of each perturbation trial [Fig 1]. Thirty-four 14-mm diameter reflective markers were attached to the body according to the Plug-in-Gait model marker set. Kinematic parameters including whole body CoM position and joint angles were calculated using the Vicon Plug-in-Gait body model. The outcome variables were then calculated from the exported Plug-in-Gait marker trajectories, CoM position and joint angles using custom software developed in MATLAB R2010a (The MathWorks, Inc., Massachusetts, USA).

Primary outcome

Postural balance during recovery was measured using the range of anteroposterior (AP) trunk sway. This primary outcome was defined between the time of contact with the hazard and the third recovery heel strike and calculated by subtracting the minimum AP trunk angle from the maximum AP trunk angle [Fig 1]. Larger AP sway (>20°) indicates more disrupted balance. Peak sway typically occurs after the 1st recovery step and therefore both the last pre-hazard approach step and the first recovery step gait kinematics may strongly influence this primary outcome.

Secondary outcomes

The secondary outcomes describe the gait kinematics for the last approach step (used to assess anticipatory adjustments) and the first recovery step (used to assess recovery reactions). The gait parameters used are similar to those described by previously (Bhatt et al., 2006; Bierbaum et al., 2011; Cham and Redfern, 2002; Chambers and Cham, 2007; Moyer et al., 2006; Pai et al., 2010; Pai et al., 2014; Pijnappels et al., 2004; Wang et al., 2011, 2012). Foot contact angle relative to the ground (deg), knee flexion angle of the stepping leg (deg) and CoM position (cm) and...
CoM velocity (cm/s) were taken from the Plug-in-Gait model at first contact of the stepping foot. A larger foot contact angle indicates a more dorsiflexed orientation at heel strike. Smaller knee flexion angle indicates a more extended knee posture of stepping leg at heel strike. Maximum slipping speed (cm/s), step length (cm) and toe clearance from the ground at mid swing phase (cm) were calculated from the foot markers.

Margin of stability (MoS) was calculated at first contact of the stepping foot and was the anterior-posterior displacement (cm) between the closest edge of the base of support (BoS) and the extrapolated CoM in the sagittal plane (Hof et al., 2005). BoS boundaries were defined during dual stance by the most posterior aspect of the rear foot and the most anterior aspect of the front foot (as determined from the heel and toe locations at each dual stance epoch). The extrapolated CoM was based on an inverted pendulum model and calculated from the vertical projection of the CoM, plus its velocity relative to the support surface times a factor (square root l/g); where l is leg length and g acceleration of gravity (Hof et al., 2005).

Changes in CoM height (cm) were calculated to quantify the contribution of lower limb support from the stance limb. For the trip recovery steps and the approach steps, the change in CoM height was calculated by subtracting the minimum whole body CoM height in dual stance from the maximum whole body CoM height in swing phase. Maximum and minimum CoM heights between consecutive heel strikes were found using MATLAB’s min() and max() functions. For slip recovery, the change in whole body CoM height was calculated over the slip duration.

CoM relative to stepping foot (cm) was calculated at first foot contact using the distance between the CoM and stepping ankle joint centre in the sagittal plane (a negative value is usual and indicates the CoM is posterior to the stepping foot). CoM relative to stance foot (cm) was calculated at the end of swing phase using the distance between the stance ankle joint centre and the CoM (a positive value is usual and indicates the CoM is anterior to the stance foot).

2.5 Statistical analysis
We hypothesized improved balance recovery after repeated exposures would be observed as a reduction in the range of AP trunk sway (primary outcome). Our hypothesis was assessed using a paired t-test comparing the baseline exposure (first exposure for the first condition; 1.Rht) and last exposure for the last condition (12.Rnd) for both trips [Figs. 1A & 2A] and slips [Figs. 1B & 2B]. Significance was set at \( p \leq 0.05 \) and Cohen’s \( d \) was used to determine the effect sizes. Transfer from right leg to left leg exposure was assessed by comparing the range of AP trunk sway for the baseline first right leg exposure (1.Rht) with the first left leg exposure (5.Lft). Fixed to random location transfer was assessed by comparing the baseline first fixed exposure (1.Rht) with the first exposure in a random location (9.Rnd).

To investigate the biomechanical mechanisms important for successful balance recovery from unexpected hazards, data from the first exposures to each new condition were analyzed. This comprised the first right leg exposure (1.Rht), the first left leg exposure (5.Lft) and the first exposure to a randomly placed hazard (9.Rnd). Pearson’s correlation coefficients were used to assess the influence of the secondary outcomes (describing the approach gait and recovery step kinematics) on the primary outcome (range of AP trunk sway; where reduced sway indicates better balance recovery). Significance was set at \( p \leq 0.05 \). Pearson’s \( r \)-values of \( >0.7 \) or \( <0.7 \) indicated a strong; \( >0.5 \) or \( <0.5 \) moderate; or \( >0.3 \) or \( <0.3 \) weak correlation. Data from slips and trips were analyzed separately.

3. Results
3.1 Reduced range of AP trunk sway following repeated exposure to hazards (primary outcome)
Changes in AP trunk sway over three recovery steps following trip and slip hazards were averaged for the group and presented in [Fig. 1]. Trip hazards induced a forward loss of balance (as measured by a positive trunk angle or trunk flexion), which peaked at around 400 ms after the perturbation [Fig. 1A]. Slip hazards induced a backward loss of balance (as measured by a negative trunk angle or trunk extension), which was followed by a forward loss of balance during the subsequent recovery steps [Fig. 1B]. For both trips and slips, the complete recovery of trunk angle took multiple steps. Balance recovery was significantly improved through repeated exposures (Figure 1 blue line, Tables 1 & 2). The overall effects were larger for trips (Cohen’s \( d -1.24 \)) than slips (Cohen’s \( d -0.93 \)).
Fig. 1 Differences in balance recovery (positive and negative trunk angles) for three steps following exposures to trip (A) and slip (B) hazards. A marked reduction in anteroposterior trunk sway was observed between first (red lines) and last (blue lines) exposures. Mean global trunk angles for all participants and the 95% confidence interval of the mean are presented. Margin of stability (MOS) was measured at each heel strike. Time zero is the onset of the trip [Fig. 1A] and slip [Fig 1B] respectively.

### Table 1 Improved trunk control after repeated exposure to trips (* significant p≤0.05 training and transfer effects)

| Trip recovery                  | Mean  | Std dev | Δ from baseline | p-value | Cohen's d |
|--------------------------------|-------|---------|-----------------|---------|-----------|
| Trunk sway (anteroposterior range [°]) |       |         |                 |         |           |
| (1) First exposure right leg (baseline) | 26.7  | 11.1    |                 |         |           |
| (5) First exposure left leg (left-right transfer) | 23.5  | 10.5    | 0.30            | -0.30   |           |
| (9) First random location (fixed-random transfer) | 14.7  | 9.5     | 0.04            | -1.12*  |           |
| (12) Last exposure right leg (overall effect) | 14.3  | 8.8     | 0.01            | -1.24*  |           |

### Table 2 Improved trunk control after repeated exposure to slips (* significant p≤0.05 training effect)

| Slip recovery                  | Mean  | Std dev | Δ from baseline | p-value | Cohen's d |
|--------------------------------|-------|---------|-----------------|---------|-----------|
| Trunk sway (anteroposterior range [°]) |       |         |                 |         |           |
| (1) First exposure right leg (baseline) | 32.7  | 16.2    |                 |         |           |
| (5) First exposure left leg (left-right transfer) | 36.1  | 18.6    | 0.60            | 0.20    |           |
| (9) First random location (fixed-random transfer) | 25.7  | 9.4     | 0.17            | -0.40   |           |
| (12) Last exposure right leg (overall effect) | 19.0  | 13.3    | 0.05            | -0.93*  |           |

3.3 Transfer effects: left to right legs and fixed to random locations

Figure 2 shows the progression of hazard exposures and balance recovery for trips [Fig. 2A] and slips [Fig. 2B]. For both trips and slips characteristic “saw tooth” trends were observed for improved balance recovery, whereby reduced AP trunk sway was generally observed within each condition; after repeated right leg exposures (Fig 2A & 2B: 1.Rht to 4.Rht), repeated left leg exposures (Fig 2: 5.Lft to 8.Lft) and repeated exposures in random locations (9.Rnd to 12.Rnd). Improvements in reactive balance recovery, however, did not always transfer between legs or conditions as demonstrated by an increase in AP trunk sway for the first unexpected left leg exposure (4.Rht to 5.Lft). For trips only, a significant transfer from fixed to random location (Fig 2A: 1.Rht to 9.Rnd) was observed (Table 1, Cohen’s d -1.12); whereby exposing both left and right legs at fixed locations transferred to improved balance recovery for the first unexpected trip presented in a random location.
Fig. 2 Trunk sway range, showing improved balance recovery after repeated exposures to trip (A) and slip (B) hazards. Mean anteroposterior trunk sway range and the 95% confidence interval of the mean for the first and last exposures to each condition are presented. 1.Rht to 4.Rht – right leg hazard in fixed location. 5.Lft to 8.Lft – left leg hazard in fixed location. 9.Rnd to 12.Rnd – left or right leg hazards in near, middle or far locations.

3.4 Biomechanical mechanisms associated with reduced AP trunk sway following trips

For the walks with unexpected trip hazards, the kinematics of the first recovery step affected balance recovery. Reduced range of AP trunk sway during balance recovery was strongly correlated with a posterior position of the CoM relative to the stepping foot \((r = 0.91)\) at the first recovery heel strike and increased margin of stability \((r = -0.82)\) at the first recovery heel strike (Table 3, col 3). Reduced AP trunk sway was also correlated with reduced knee flexion in the stepping limb \((r = 0.76)\) and increased foot contact angle \((r = -0.42)\) at first contact, which likely contributed to the longer first recovery step length \((r = -0.71)\). The contributions of the support and swing limbs in clearing the trip hazard may be assessed by the moderate correlations between reduced AP trunk sway and increased change in CoM height \((r = -0.52)\) and higher toe clearance \((r = -0.66)\) during the first recovery step. For unexpected trip hazards, the kinematics of the last approach step had no detectable effect on balance recovery (Table 3, col 2).

Table 3 Biomechanical factors associated with reduced trunk sway following unexpected trips (* sig \(p\leq 0.05\) correlation)

| Trip recovery Correlations with trunk sway | Last approach pre-trip step Pearson’s r | 1st Recovery step Pearson’s r |
|--------------------------------------------|---------------------------------------|-------------------------------|
| CoM relative to stepping foot               | 0.08                                  | 0.91*                         |
| Margin of stability                         | -0.18                                 | -0.82*                        |
| Knee flexion (stepping leg)                | 0.12                                  | 0.76*                         |
| Step length                                 | -0.04                                 | -0.71*                        |
| Toe clearance                               | -0.04                                 | -0.66*                        |
| Change in CoM height                        | -0.07                                 | -0.52*                        |
| Foot contact angle                          | -0.18                                 | -0.42*                        |
| Step time                                   | -0.11                                 | -0.39*                        |
| CoM relative to stance foot                 | 0.07                                  | -0.22                         |
| CoM velocity                                | 0.18                                  | 0.16                          |

3.5 Biomechanical mechanisms associated with reduced AP trunk sway following slips

For the walks with unexpected slip hazards, reduced range of AP trunk sway during balance recovery was moderately correlated with reduced slipping speed of the stance foot \((r = 0.54)\). At first contact of the recovery step, reduced AP trunk sway was also weakly correlated with an anterior position of the CoM relative to the stance foot \((r = -0.39)\) and reduced knee flexion of the stepping limb \((r = 0.38, \text{Table 4})\). For slip hazards, the kinematics of the approach step had no significant effect on balance recovery (Table 4, col 2).
Table 4 Biomechanical factors associated with reduced trunk sway following unexpected slips (* sig p≤0.05 correlation)

| Slip recovery | Correlations with trunk sway | Last approach pre-slip step | 1st Recovery step | Pearson’s r | Pearson’s r |
|---------------|-----------------------------|-----------------------------|-------------------|-------------|-------------|
|          |                             |                              |                   |             |             |
| Slipping speed (stance foot) |                             |                              |                   | 0.54*       |             |
| CoM relative to stance (slipping) foot |                             |                              |                   | 0.18       | -0.39*      |
| Knee flexion (stepping leg) |                             |                              |                   | 0.06       | 0.38*       |
| Step time |                             |                              |                   | 0.31       | -0.21       |
| Step length |                             |                              |                   | 0.25       | -0.31       |
| CoM velocity |                             |                              |                   | 0.08       | -0.26       |
| Margin of stability |                             |                              |                   | 0.09       | -0.26       |
| CoM relative to stepping foot |                             |                              |                   | -0.26      | 0.16        |
| Change in CoM height |                             |                              |                   | 0.14       | -0.20       |
| Foot contact angle |                             |                              |                   | 0.20       | -0.02       |
| Toe clearance |                             |                              |                   | -0.09      | -0.02       |

Fig. 3 Trunk sway plotted against CoM position and Pearson’s correlations demonstrating the importance of reactive CoM, trunk and balance control during recovery from unexpected trips (A) and slips (B). For trips [Fig. 3A], better balance recovery (reduced trunk sway) was achieved by a more posterior CoM position relative to the stepping foot. For slips [Fig. 3B] the direction of the trend was reversed and a less posterior CoM position relative to the stance foot was favorable.

4. Discussion

4.1 Biomechanical mechanisms

The purpose of this study was to investigate the biomechanical mechanisms associated with balance recovery from the first exposures to randomly presented and located unexpected slip and trip hazards. The primary outcome representing balance recovery was the range of AP trunk sway in the sagittal plane over the three recovery steps after the trip [Fig. 1A] and slip [Fig. 1B] hazards. The dramatic reduction in trunk sway between the first and last exposures for trips (Cohen’s d -1.24) and slips (Cohen’s d -0.93) indicates that reactive balance recovery in the young cohort improved after repeated exposures [Figs. 1 & 2]. Our findings agree with research by other groups who have also reported large improvements in recovery from both trips and slips in a single session (Bhatt et al., 2006; Bierbaum et al., 2011; Cham and Redfern, 2002; Chambers and Cham, 2007; Moyer et al., 2006; Pai et al., 2010; Wang et al., 2011, 2012). In contrast to previous research; however, we minimized the potential influence of anticipatory adjustments, which in previous experimental protocols have included reduced approach velocity, shorter step lengths, reduced foot angle at heel strike, greater knee flexion and a more anterior CoM position (Bhatt et al., 2006; Cham and Redfern, 2002;
Chambers and Cham, 2007; Wang et al., 2011, 2012). Different to previous research, our experimental protocol used prompts to maintain constant cadence and step length, which were combined with the placement of undetectable slip and trip hazards in different locations. We hypothesized this would reduce the risk of any anticipatory adjustments (during the approach steps) biasing our novel assessments of reactive balance recovery (Bohm et al., 2015). Our hypothesis was confirmed by the lack of any significant correlations between the approach kinematics and balance recovery [Tables 3 & 4, cols 2].

Previous research has generally focused on the first recovery step following the perturbation, but in this experiment we examined balance recovery over three steps. The balance perturbations caused by trips and slips were different. In agreement with previous research (Pijnappels et al., 2004), contact of the swing foot with the hidden trip hazard caused an increase in forward angular momentum, which was observed as an increase in trunk angle [Fig. 1A]. For trip hazards, maximum forward rotation of the trunk generally occurred between contact with the hazard and the second recovery heel strike and complete recovery to an upright position often took multiple steps [Fig. 1A]. For slip hazards, stepping on the slip hazard caused a backward loss of balance, which was observed as a negative trunk angle [Fig. 1B] and agrees with previous research (Bhatt et al., 2006; Cham and Redfern, 2002; Chambers and Cham, 2007; Moyer et al., 2006; Pai et al., 2010; Wang et al., 2011). Few studies have examined what happens beyond the first recovery step and after the slip ends. Our study showed that on average, the 70cm slip lasted 500ms; hitting the end of the linear bearings somewhere between the first and second recovery steps. This impact caused an external torque and associated reversal in angular momentum, which was observed as an increasingly positive trunk angle [Fig. 1B]. This situation may be common in real life scenarios when the slipping foot reaches the end of a slippery surface.

Importantly, the difference in perturbation caused by trips and slips necessitates an opposing response to control the CoM during the first recovery step [Fig. 3A]. For trips, better balance recovery (reduced AP trunk sway) was achieved when participants positioned their CoM more posterior relative to the stepping foot at heel strike [Fig. 3A]. For slips the trend was reversed; better balance recovery was achieved when participants positioned their CoM less posterior relative to the stance (sliding) foot [Fig. 3B]. Because of these differences, exposing participants to both unexpected trips and slips simultaneously limits the effectiveness of making anticipatory postural adjustments (prior to the hazard) and therefore maximizes the reactive CoM control required (after the hazard onset).

The biomechanical mechanisms underpinning optimal balance recovery from unexpected trips appear to be strongly correlated \((r = 0.91, \text{Table 3})\) with positioning the first recovery heel strike as far in front of the CoM as practical [Fig. 3A, negative CoM relative to stepping foot]. The large lever arm created by the posterior CoM position may enable a greater breaking torque to halt the forward angular momentum caused by the initial contact with the trip hazard. The optimum recovery step also requires that there is: (i) sufficient hip flexion, knee flexion and ankle dorsi-flexion of the swing leg for the toe to clear the hazard; (ii) synergistic activation of the stance limb extensors to lift the CoM vertically; and (iii) activation of the core muscle to maintain an upright trunk and a more posterior CoM position. The optimum response therefore requires both early activation and a coordinated response from multiple muscle groups.

The biomechanical mechanisms underpinning optimal reactive balance recovery from unexpected slips appear to be different from the biomechanical mechanisms involved when the slip location is known in advance. Previous experiments have shown that anticipation of a slip hazard can result in a 16-33% reduction in the required coefficient of friction (and therefore reduced slipping speed). Such anticipation has been related to reduced foot loading speed, a shorter approach step, reduced foot angle at heel strike, greater knee flexion, and a more forward CoM position (Bhatt et al., 2006; Wang et al., 2011, 2012). In our experiment we observed no significant correlations with any of these kinematics during the approach step (Table 4), but a moderate correlation was observed between reduced trunk sway and reduced slipping speed \((r=0.54, \text{Table 4})\). The biomechanical mechanisms for optimum reactive balance recovery appear to depend on maintaining the CoM above or in front of the slipping foot (Fig. 3B). Maintaining the CoM above the slipping foot reduces the angle between the CoM and the base of support, which would reduce the required coefficient of friction and therefore how fast the slipping foot accelerates. The differences in reactive balance recovery to unexpected slips in our experiment appear to be mostly related to this control of slipping speed.
Although the mechanisms for reactive control of slipping speed are not completely understood, based on a review of the literature we hypothesize that neuromuscular responses may be important. Fast acting reactive responses opposing the slip induced deviation of the ankle from its normal trajectory (onset within 50-100ms of heel strike) have been observed in response to short 8cm translations while walking (Nashner, 1980). Slower acting muscle co-contractions at the ankle and knee of the stance leg (onset 175ms to 240ms) have also been related to reduced slip severity (Chambers and Cham, 2007). Together with activation of core muscles these reactive neuromuscular mechanisms may have acted to maintain the CoM above the sliding foot and keep the trunk upright. Future experiments should therefore also include measurement of muscle activity.

4.1 Limitations and implications for future fall prevention training programs
Although reactive balance recovery was improved in our young cohort; further research is required to determine if this type of experimental protocol that incorporates a high degree of uncertainty and requires rapid reactive movements could also improve balance recovery in elderly people and comprise an efficacious fall prevention intervention for this group. This may be possible, as there may be sufficient biomechanical similarities between reactive recovery from trip hazards and step training programs (Mansfield et al., 2015; Okubo et al., 2017). Reactive balance recovery training, however, requires specialized equipment to simulate rapid deviations in joint angles from a normal gait trajectory and illicit the appropriate neuromuscular responses, which may hinder translation into practice. Further, the current protocol may only be suitable for ‘active’ older people who suffer falls due to a high exposure to trip and slip hazards encountered during their daily routines (Brodie et al., 2017; O’Loughlin et al., 1993; Okubo et al., 2015). For frail older people, the protocol could be adapted to also train the appropriate anticipatory adjustments through the use of more predictable and progressive hazard exposure, together with education to avoid hazardous terrain. Further research should investigate how long reactive balance training effects last, if supplementary strength training is required and how often reactive balance training should be repeated in elderly people.

5. Conclusions
The biomechanical mechanisms and reactive centre-of-mass control required for the successful balance recovery from trips and slips are different. During recovery from unexpected trips, sufficient toe-clearance and a longer first recovery step act to position the centre-of-mass more posteriorly relative to the stepping foot, which results in a greater breaking torque to halt the forward angular momentum caused by the trip hazard. During recovery from unexpected slips, reactive balance control is required to maintain the CoM above or in front of the slipping foot, which results in reduced shear forces and reduced acceleration of the slipping foot. Future training protocols should therefore include exposure to both trips and slips using specialized equipment to minimise predictive changes and maximise improvements in reactive responses. For unexpected trips, a longer first recovery step length appears easier to train than the control of slipping speed and center-of-mass position required to optimize reactive balance recovery from unexpected slips. Further research is required to determine the neuromuscular mechanisms responsible for optimum reactive balance recovery; the relative importance of reactive balance recovery versus anticipatory postural adjustments for preventing falls; if reactive balance recovery in older people at risk of falls can be trained and how long training effects may last.

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