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Feet kinematics upon slipping discriminate between recoveries and three types of slip-induced falls

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ABSTRACT

This study investigated the relationship between feet kinematics upon slipping while walking and the outcome of the slip. Seventy-one slips (induced by walking over an unexpectedly slippery surface) were analysed, which included 37 recoveries, 16 feet-split falls, 11 feet-forward falls and seven lateral falls. Feet kinematics differed between recoveries and three types of slip-induced falls, and a discriminant model including six measures of feet kinematics correctly predicted 87% of slip outcomes. Two potentially modifiable characteristics of the feet kinematics upon slipping that can improve the likelihood of successfully averting a fall were identified: (1) quickly arresting the motion of the slipping foot and (2) a recovery step that places the trailing toe approximately 0–10% body height anterior to the sacrum. These results may inform the development of task-specific balance training interventions that promote favourable recovery responses to slipping.

Practitioner Summary: This study investigated the relationship between feet movements upon slipping and outcomes of the slip. Potentially modifiable characteristics that can reduce the likelihood of falling were: (1) quickly arresting slipping foot motion and (2) a recovery step that places the trailing toe approximately 0–10% body height anterior to the sacrum.

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KEYWORDS
Slips; falls; balance; training; biomechanics

Introduction

Occupational slips, trips and falls are a significant public health concern. Slips, trips and falls accounted for 27% of injuries requiring days away from work in 2011 (Bureau of Labor Statistics 2015) and nearly 17% of all fatal occupational injuries in 2015 (Bureau of Labor Statistics 2016). Falls due to slipping are particularly concerning, as slips are estimated to cause 40–50% of all occupational fall-related injuries (Courtney et al. 2001).

A common slip scenario occurs at heel contact while walking, when insufficient frictional forces under the heel result in the foot unexpectedly slipping forward. Reactive responses of the slipping and trailing (non-slipping or unperturbed) feet attempt to arrest this motion, re-establish a stable base of support and avert a fall. Typical reactive responses in the slipping limb involve hip extension and knee flexion, in an attempt to decelerate the slipping foot (Cham and Redfern 2001). Reactive responses in the trailing limb also play a role in averting a fall by altering the base of support (Moyer, Redfern, and Cham 2009; You et al. 2001). The trailing limb commonly executes a recovery step, or interrupted swing phase, following slip onset, where the trailing foot is re-positioned on the ground via a hip and knee extensor strategy (Marigold, Bethune, and Patla 2003; Yang et al. 2012). Repositioning the trailing foot under the torso provides vertical support to help arrest the fall (Marigold, Bethune, and Patla 2003).

The influence of the reactive response on the outcome of a slip remains unclear. The outcome of a slip can be a successful recovery if a fall is averted, or one of three types of falls: feet-split falls, feet-forward falls and lateral falls (Moyer, Redfern, and Cham 2009; Smeesters, Hayes, and McMahon 2001; Troy et al. 2008; Yang et al. 2012). Moyer, Redfern, and Cham (2009) categorised the trailing limb response into four groups based upon trailing foot kinematics, but did not compare these responses between recoveries and falls. Troy et al. (2008) identified the velocity of the slipping foot relative to the centre of mass (COM)

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and the lateral placement of the trailing foot, both at completion of the recovery step, as two characteristics of the recovery response that influence slip-induced fall risk (Troy et al. 2008). Yang et al. (2012) reported that feet-forward falls resulted from longer recovery steps (in both time and distance), while feet-split falls resulted from unilateral slips where only one foot experienced a slip. Wang et al. (2017) reported the positioning of the trailing foot after the first recovery step to predict feet-splits or feet-forward fall with 90.8% accuracy, but did not relate this positioning to recoveries and falls. These studies by Yang et al. (2012) and Wang et al. (2017) employed a sliding platform that only moved anteriorly or posteriorly to experimentally induce slips. While a sliding platform is useful for constraining or controlling slip characteristics, constraining the motion of the slipping foot may inadvertently and artificially influence slipping foot kinematics or fall direction when compared to slips on an unconstrained, low-friction surface (Albert, Moyer, and Beschorner 2017; Troy and Grabiner 2006). Moreover, these studies do not clearly associate characteristics of the reactive response with slip outcome.

The goals of this study were twofold. First, we investigated differences in slipping and trailing feet kinematics between recoveries and three types of slip-induced falls (feet-split falls, feet-forward falls and lateral falls). Second, we identified characteristics of the slipping and trailing feet kinematics that discriminated between these four slip outcomes. Slips were induced in a laboratory using a contaminated slippery surface in an effort to elicit ecologically valid, unconstrained slips. Our first hypothesis was that feet kinematics upon slipping would differ between recoveries and three types of falls. Our second hypothesis was that modifiable, performance-related feet kinematics would discriminate between the four outcomes. The results from this work will help to identify the characteristics of effective reactive responses that reduce the likelihood of falling, and could aid in the development of interventions that facilitate effective reactive responses to slips, such as task-specific, perturbation-based balance training (Allin, Nussbaum, and Madigan 2017; Pai and Bhatt 2007; Pavol, Runtz, and Pai 2004; Wang et al. 2011; Yang, Bhatt, and Pai 2013; Yang, Wang, and Pai 2014).

Methods

Subjects included 108 adults (age: 18–66 years, BMI: 17.1–45.1 kg/m^2, 57 women), using data combined from two studies. Sixty-nine subjects were obtained from a previous study (Allin et al. 2016; age: 18–29, 50–66 years; BMI: 17.7–26.3, 29.1–45.1 kg/m^2, 37 women), and the remaining 39 young adults (aged 18–31; BMI: 17.1–34.9 kg/m^2; 20 females) participated in a subsequent study (unpublished). Subjects in both studies were recruited from the university and local community using electronic announcements, community flyers and newspaper advertisements. All subjects were screened using a medical questionnaire to exclude individuals with self-reported musculoskeletal or neurological disorders that influence gait or balance. Six subjects aged 60 and older were also required to pass a medical evaluation administered by a physician. This evaluation excluded participants with any neurological, cardiac, respiratory, ontological or musculoskeletal disorders, and required a minimum bone density of the femoral neck of 0.65 g/cm^2 as assessed by DXA (General Electric, Lunar Digital Prodigy Advance, Madison, WI). Each study was approved by the local university Institutional Review Board.

The experimental procedure for inducing slips was identical to a prior study (Allin et al. 2016). Subjects were asked to look straight ahead and to walk at a purposeful (slightly hurried) self-selected speed along a 10-metre walkway covered in vinyl tile. Subjects were warned that they may or may not be slipped or tripped while walking, and that, in the event of a slip or trip, they should attempt to recover their balance and continue walking. After a minimum of 15 walking trials, subjects were unexpectedly slipped. The slip was induced when the heel of the dominant foot contacted a 0.9 × 0.9-m area located 6 m (or 6–7 steps) from the end of the walkway, over which 50 mL of vegetable oil was uniformly spread. The vegetable oil was applied while subjects faced away from the walkway and watched television while wearing wireless headphones, so that they were unaware that a slip was to occur. Laboratory lights were dimmed to reduce reflections on the slippery surface. All subjects wore the same model of dress shoes with soles made of thermoplastic rubber (A82 Shore hardness) to prevent any differences related to the shoe-floor interface. To prevent impact with the floor in the event of an unsuccessful recovery, subjects wore a safety harness tethered by a lanyard to a track above the walkway. The length of the lanyard was adjusted so that subjects' knees were approximately 15 cm from the floor when fully supported by the harness and attempting to kneel. The subjects' hands could not touch the floor at this length.

Body kinematics and forces applied to the harness were measured during all trials. The three-dimensional locations of retro-reflective markers – placed bilaterally on the calcaneus, hallux, acromion process, greater trochanter and one marker on the sacrum – were sampled at 100 Hz using either a Vicon MX six-camera motion capture system (Vicon Motion Systems, Denver, CO) or a Qualisys eight-camera motion capture system (Qualisys North America, Inc., Buffalo Grove, IL), and low-pass filtered at 12 Hz (second-order zero-phase-lag Butterworth filter). Forces applied to the harness were sampled at 1000 Hz from a uniaxial load cell (Cooper Instruments and Systems, Warrenton, VA) and low-pass filtered at 40 Hz (fourth-order zero-phase-lag Butterworth filter).

Slips were initially screened to remove those that did not elicit an obvious interruption to gait. Twenty-one slips were excluded because the trailing heel was anterior to the slipping heel at touchdown of the recovery step (our indication that there was no obvious interruption to gait). Nine additional slips were excluded because, during the recovery step, the tip of the trailing toe was impeded by a gap between the walkway and the leading edge of a force platform, which may have affected the execution of the recovery step. Slip outcome was then identified as either a 'recovery,' if a one-second moving average of the harness load was < 4.5% body weight (BW) during the entire slip, or a 'fall', if the peak harness load was ≥ 30% BW (Yang and Pai 2011). Seven slips did not satisfy either of these definitions and thus were deemed 'harness-assisted' and excluded from further analysis. After these exclusions, 71 slips remained for further analysis.

Each fall was then categorised as either a feet-split fall, feet-forward fall, or lateral fall using a Euclidean distance nearest neighbour method (Hastie, Tibshirani, and Friedman 2009). In short, this method involved first categorising slips that had unambiguous fall types. Then, using four measures of trunk and feet kinematics at harness-arrest (when the force applied to the harness first exceeded 30% BW) along with the previously categorised falls, the Euclidean distance nearest neighbour method systematically categorised any remaining slips with a more ambiguous fall type. This method is described in more detail in the Supplemental Material.

Several continuous dependent variables were obtained to describe gait characteristics, slip severity and feet kinematics upon slipping. Variables related to gait characteristics included gait speed (mean anterior velocity of the sacrum marker) and step length (mean distance between consecutive heel strikes) during all steps prior to the slip during the slip trial. Gait speed and step length were normalised to body height for statistical analysis, but reported in metres/second and metres, respectively, for utility. Slip severity was quantified based on slipping foot kinematics from the heel contact immediately prior to slip onset (subsequently referred to as 'heel contact') to touch-down of the trailing foot during the recovery step (subsequently referred to as 'touch-down'); specific variables were peak slip speed and slip distance in both the anteroposterior (AP) and mediolateral (ML) directions. Temporal characteristics of feet kinematics included the time from heel contact to lift-off of the trailing foot during the recovery step (subsequently referred to as 'lift-off'), and duration from lift-off to touch-down (similar to those used by Troy and Grabiner (2006); Troy et al. (2008); and Moyer, Redfern, and Cham (2009)). The times at which heel contact and lift-off occurred were identified using velocities of the heel and toe markers (O'Connor et al. 2007). The time at which touch-down occurred was identified using the acceleration of the trailing toe marker. All event times were verified visually using the kinematic data.

Spatial characteristics of feet kinematics were adopted from Troy et al. (2008), Yang, Anderson, and Pai (2008) and Yang et al. (2012). There characteristics were determined at lift-off and touch-down in both AP and ML directions, and expressed as per cent body height (%bh). Spacial characteristics of feet kinematics included heel-to-heel distance (distance between the trailing and slipping heels), slipping heel position relative to the sacrum, and trailing toe position relative to the sacrum (Figure 1). We referenced the sacrum for these measures, rather than the whole-body centre of mass as used in previous studies (Troy et al. 2008; Yang, Anderson, and Pai 2008), because of ease of measurement and the high correlation between these two landmarks during gait and slip recovery (Yang and Pai 2014). Spatial characteristics of feet kinematics also included the mean speed of the slipping heel and trailing toe during the 50 ms immediately following touch-down in both the ML (absolute value) and AP directions. One

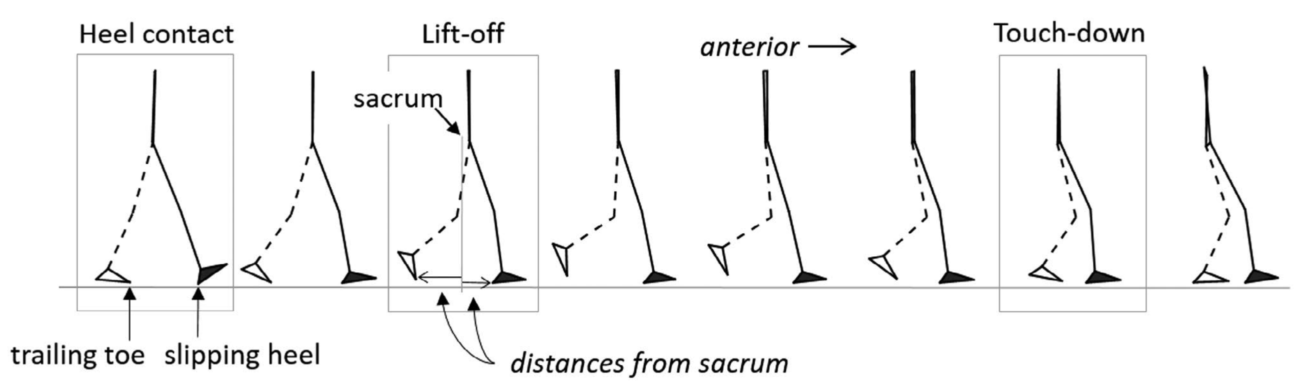

Figure 1. Spatial characteristics of the slipping (black) and trailing (white) feet were measured at lift-off and touch-down of the trailing foot during the recovery step.

nominal variable was placement of the trailing toe onto or off of the contaminant, which was determined by comparing the trailing toe position at touch-down to the location of the contaminated area on the walkway.

Dunnett's tests were used to compare continuous variables between recoveries and each type of fall, with recoveries used as the control condition and the three fall types used as a treatment conditions. Fisher's Exact tests were used to compare placement of the trailing foot on or off the slippery surface between recoveries and each type of fall, and using a Bonferroni correction. Feet kinematic measures that were statistically significant were entered into a forward stepwise discriminant analysis to identify a subset of variables that can discriminate between the four outcomes. For each variable that was significant in the final discriminant model, a univariate logistic regression analysis was used to calculate the odds ratios for experiencing each type of fall compared to recoveries. All statistical calculations were performed using JMP Pro 12 (SAS Institute Inc., Cary, NC) and $\alpha = 0.05$.

Results

The 71 slips that were analysed included 37 recoveries, 16 feet-split falls, 11 feet-forward falls and 7 lateral falls (Figure 2). Subject age and BMI did not differ significantly between recoveries and the three fall types (Table 1). The three fall types differed from recoveries with respect to gait characteristics, slip severity, feet kinematics and placement of the trailing foot onto the slippery surface. These differences are described in the subsequent three paragraphs.

Feet-split falls were characterised by a larger AP distance between the feet after slipping, but several other differences from recoveries were found. Regarding gait characteristics prior to slipping (Table 1), gait speed was 0.09 m/s faster (p = 0.009) and step length was 1.4 cm

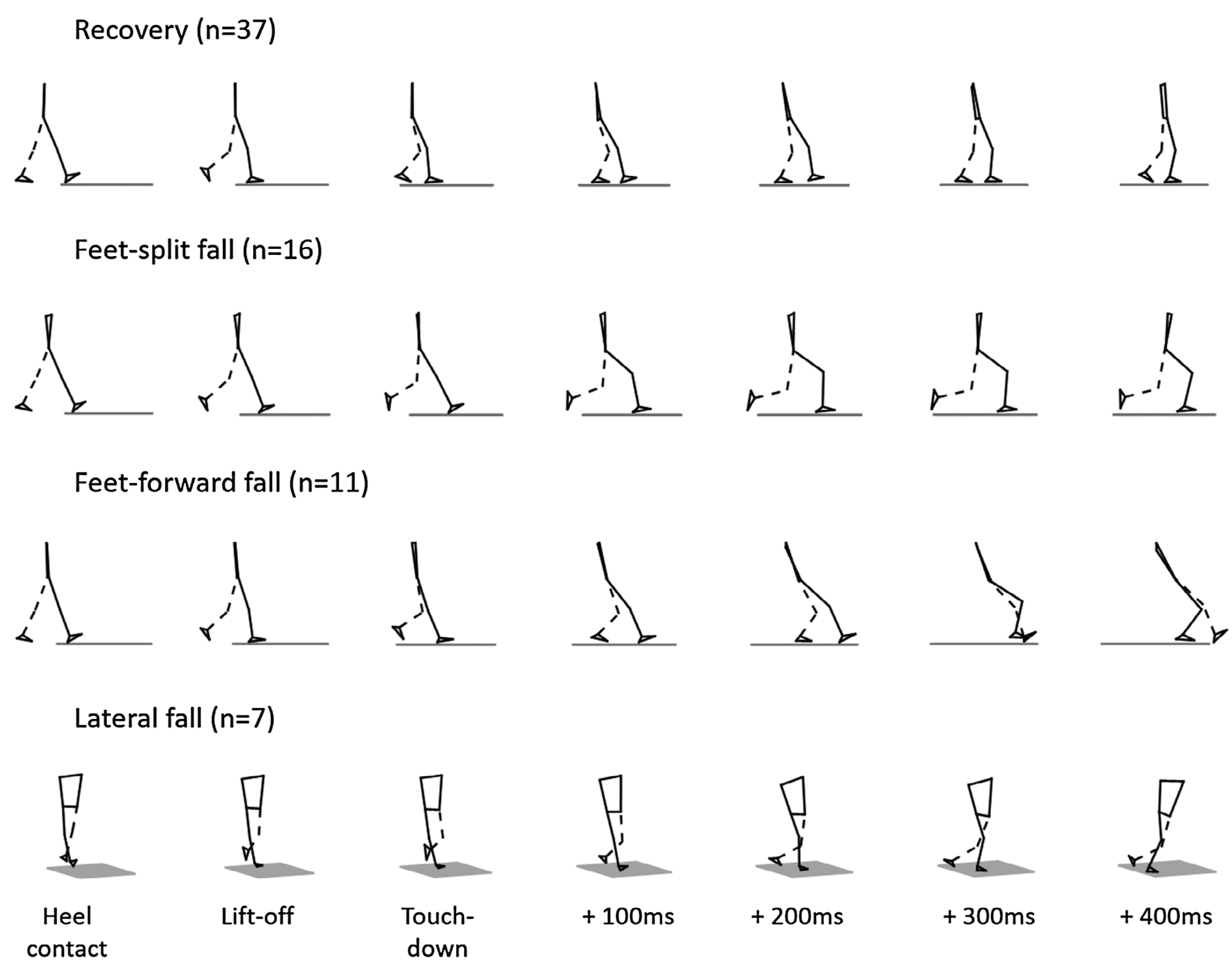

Figure 2. Examples of each type of slip outcome, where the dashed line indicates the trailing (non-slipping) limb.
Notes: The initial frame of each outcome is the instant of heel contact on the contaminated surface, followed by lift-off of the recovery step of the trailing foot and touchdown of the recovery step of the trailing foot, and additional frames at 100 ms intervals after touch-down.

Table 1. Subject demographics, gait characteristics, and slip severity across slip outcomes (values reported as mean (SD)).

	Recoveries	Feet-split falls	Feet-forward falls	Lateral falls
	n = 37	*n* = 16	*n* = 11	*n* = 7
Age (years)	26.9 (13.1)	26.4 (14.8)	27.9 (13.2)	26.9 (12.1)
BMI (kg/m^2)	24.9 (4.9)	25.1 (4.0)	27.8 (5.8)	26.8 (6.5)
Gait Speed (m/s)	1.26 (0.11)	1.35 (0.13)	1.36 (0.16)	1.43 (0.21)
Step Length (cm)	68.2 (5.4)	69.6 (4.6)	71.9 (6.1)	74.0 (6.9)
Peak ML Slip Speed (m/s)	0.54 (0.25)	0.58 (0.27)	0.64 (0.28)	0.85 (0.24)
Peak AP Slip Speed (m/s)	1.56 (0.38)	2.53 (0.40)	2.00 (0.47)	2.42 (0.53)
ML Slip Distance (cm)	6.1 (2.8)	6.8 (3.8)	8.4 (4.0)	10.8 (3.8)
AP Slip Distance (cm)	25.5 (7.9)	43.1 (6.6)	36.1 (10.0)	42.5 (14.4)
Percent placing trailing toe onto contaminant (%)	95%	44%	100%	86%

Note: Shaded values represent statistically significant difference compared to recoveries.

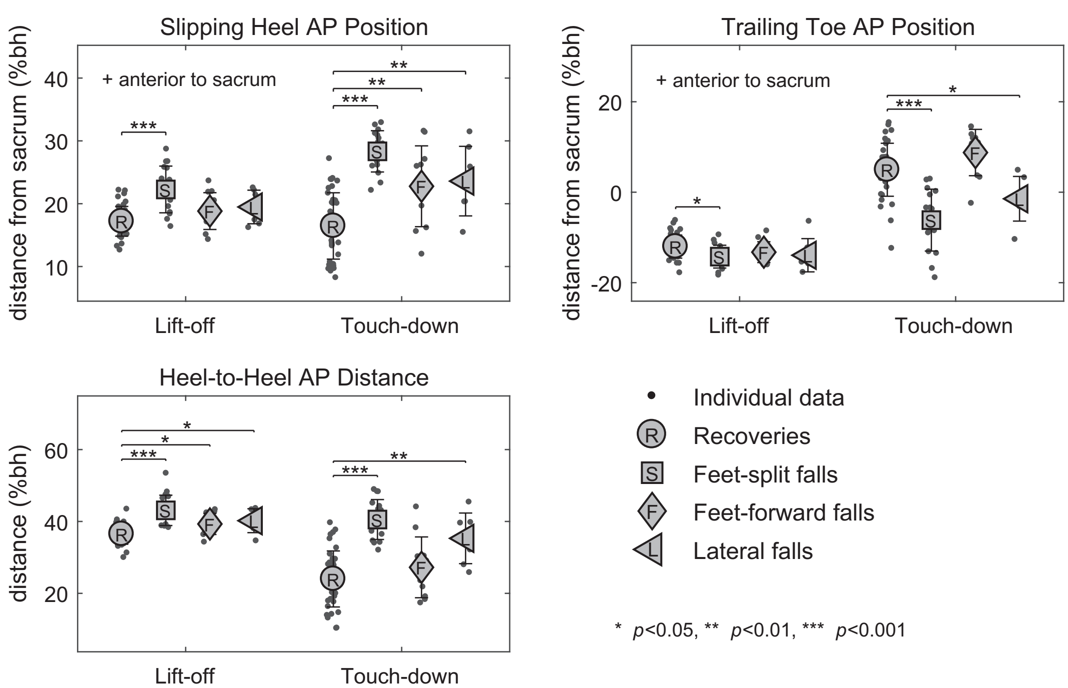

Figure 3. Measures of slipping and trailing feet kinematics and recovery responses that differed between falls and recoveries, expressed as per cent body height (%bh).
Notes: Dark symbols represent mean values for each group, error bars are standard deviations, and asterisks indicate statistically significant differences compared to recoveries.

longer ($p < 0.001$) compared to recoveries. Regarding slip severity (Table 1), peak AP slip speed was 0.97 m/s faster ($p < 0.001$) and AP slip distance was 17.6 cm longer ($p < 0.001$) compared to recoveries. Regarding feet kinematics (Figure 3), heel-to-heel AP distance was 6.6%bh larger at lift-off ($p < 0.001$) and 16.5%bh larger at touch-down ($p < 0.001$) compared to recoveries. Slipping heel AP position was 5.1%bh more anterior to the sacrum at lift-off ($p < 0.001$) and 11.9%bh more anterior to the sacrum at touch-down ($p < 0.001$), compared to recoveries. Trailing toe AP position was 2.2%bh more posterior to the sacrum at lift-off ($p = 0.018$) and 11.1%bh more posterior to the sacrum at touch-down ($p < 0.001$). The mean trailing toe AP speed during the 50 ms following touch-down was 1.22 m/s slower in the anterior direction ($p < 0.001$; Figure 4), compared to recoveries. Time from heel contact to trailing foot lift-off was 18.4 ms shorter compared to recoveries ($p = 0.037$; Figure 5). Seven of 16 (44%) feet-split fallers placed the trailing toe onto the contaminated surface at touch-down (Figure 6). This proportion was lower than that of recoveries ($p < 0.001$), of which 35 of 37 (95%) placed the trailing toe onto the contaminant.

Feet-forward falls were characterised by a more anterior slipping heel position and faster anterior speed of the trailing foot after slipping, but several other differences from recoveries were found. Regarding gait characteristics prior to slipping (Table 1), step length was 3.7 cm longer ($p = 0.022$), but gait speed did not differ ($p = 0.111$),

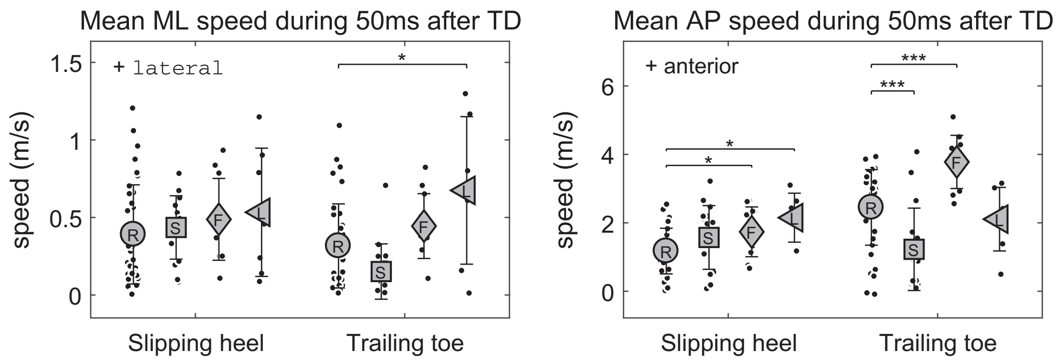

Figure 4. Mean slipping heel and trailing toe speed during the 50 ms following touch-down (TD).
Notes: Dark symbols represent mean values for each group, error bars denote standard deviations, and asterisks indicate statistically significant differences compared to recoveries (* $p<0.05$, ** $p<0.01$, *** $p<0.001$).

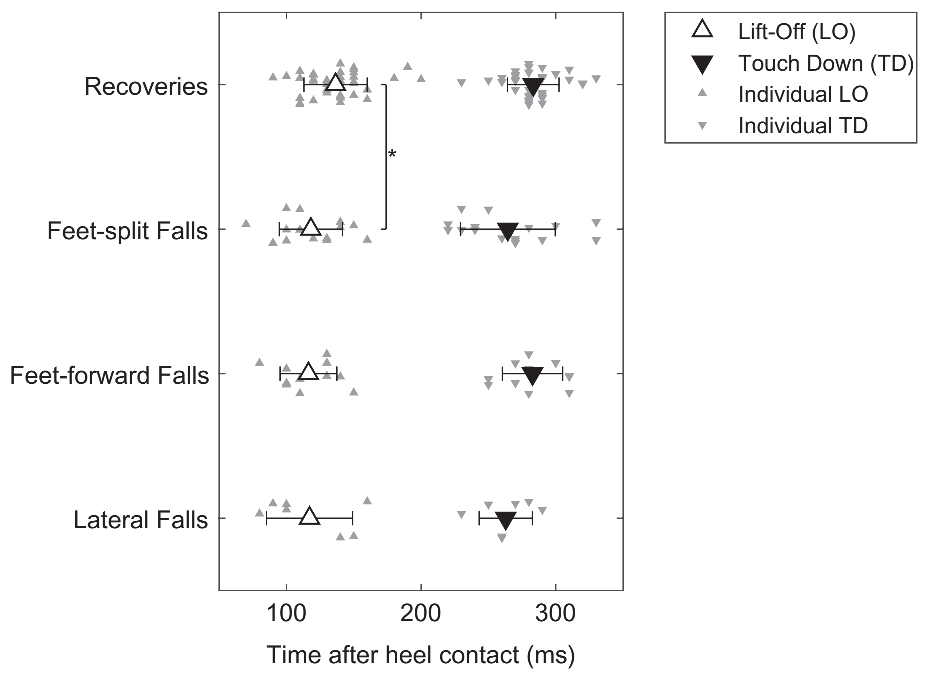

Figure 5. Time from heel contact of the slipping foot to lift-off (LO) and touch-down (TD) of the recovery step of the trailing foot (mean, standard deviation and individual subject data) for each slip outcome.
Notes: Asterisks indicate statistically significant differences compared to recoveries (* $p<0.05$) for time from heel contact to LO.

compared to recoveries. Regarding slip severity, peak AP slip speed was 0.45 m/s faster ($p = 0.007$), and AP slip distance was 10.6 cm longer ($p = 0.002$), compared to recoveries. Regarding feet kinematics (Figure 3), heel-to-heel AP distance was 2.8%bh larger at lift-off ($p = 0.042$), and slipping heel AP position was 6.3%bh more anterior at touch-down ($p = 0.002$). During the 50 ms following touch-down, the mean trailing toe AP speed was 1.33 m/s faster ($p = 0.002$), compared to recoveries. Time from heel contact to lift-off was 20.1 ms shorter (approaching significance, $p = 0.050$; Figure 5), compared to recoveries. All 11 feet-forward fallers placed the trailing toe onto the contaminant at touch-down of the recovery step, and this proportion did not differ from recoveries ($p = 0.302$; Figure 6).

Lateral falls were characterised by slipping faster and farther in the mediolateral direction and a faster mediolateral speed of the trailing foot after touch-down, but several other differences from recoveries were found. Regarding gait characteristics (Table 1), gait speed was 0.17 m/s faster ($p = 0.014$) and step length was 5.8 cm longer ($p = 0.026$) prior to slipping, compared to recoveries. Regarding slip severity (Table 1), peak ML slip speed was 0.32 m/s faster ($p = 0.012$), peak AP slip speed was 0.86 m/s faster ($p < 0.001$), ML slip distance was 4.6 cm

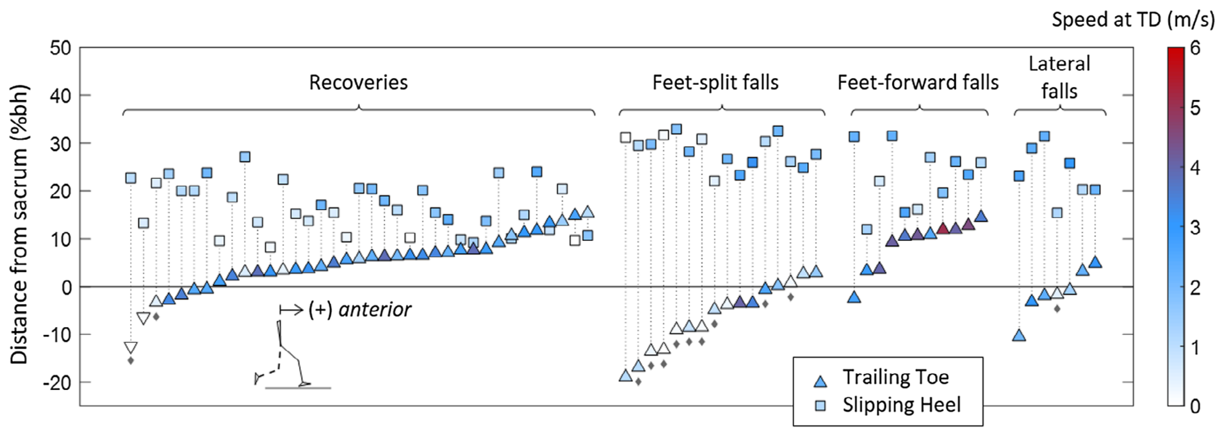

Figure 6. Slipping heel and trailing toe AP positions relative to the sacrum at touch-down (TD) for each subject, where positive values indicate a position anterior to the sacrum.
Notes: Slipping heel and trailing toe AP speed at TD were calculated as the mean anterior speed for 50 ms following TD (inverted triangles indicate posterior speed). Diamonds indicate that touch-down of the trailing toe occurred *off* the contaminated surface.

Table 2. Odds ratios and 95% confidence intervals (C.I.) for the effects of each variable included in the discriminant model on the likelihood of experiencing each type of fall compared to a recovery.

	Feet-split fall	Feet-forward fall	Lateral Fall
	Odds Ratio [95% C.I.]	Odds Ratio [95% C.I.]	Odds Ratio [95% C.I.]
Peak slip speed (+0.1 m/s)	2.04 [1.34, 3.12] $p < 0.001$	1.30 [1.07, 1.57] $p = 0.003$	1.50 [1.14, 1.96] $p < 0.001$
Trailing toe AP position at touch-down (+1%bh anterior)	0.76 [0.66, 0.89] $p < 0.001$	1.15 [0.99, 1.34] $p = 0.041$	0.83 [0.71, 0.97] $p = 0.011$
Slipping heel AP position at touch-down (+1%bh anterior)	2.13 [1.28, 3.55] $p < 0.001$	1.22 [1.06, 1.41] $p = 0.002$	1.30 [1.06, 1.61] $p = 0.002$
Heel-to-heel AP distance at touch-down (+ 1%bh)	1.45 [1.16, 1.82] $p < 0.001$	1.05 [0.97, 1.15] $p = 0.235$	1.22 [1.06, 1.42] $p < 0.001$
Trailing toe ML speed during 50 ms following touch-down (+0.1 m/s)	0.69 [0.48, 0.99] $p = 0.016$	1.20 [0.93, 1.54] $p = 0.159$	1.35 [1.05, 1.73] $p = 0.013$
Trailing toe AP speed during 50 ms following touch-down (+0.1 m/s)	0.92 [0.87, 0.97] $p < 0.001$	1.24 [1.07, 1.42] $p < 0.001$	0.97 [0.90, 1.04] $p = 0.445$

Note: Shaded values indicate significant odds ratios ($p < 0.05$).

longer (p = 0.004), and AP slip distance was 17.0 cm longer (p < 0.001), compared to recoveries. Regarding feet kinematics (Figure 3), heel-to-heel AP distance was 3.7%bh larger at lift-off (p = 0.021) and 11.3%bh larger at touch-down (p = 0.001) compared to recoveries. AP slipping heel position was 7.1%bh more anterior at touch-down (p = 0.004), and trailing toe AP position was 6.4%bh more posterior at touch-down (p = 0.031). During the 50 ms following touch-down, the mean slipping heel AP speed was 0.98 m/s faster (p = 0.007), and the mean trailing toe ML speed was 0.36 m/s faster (p = 0.006), compared to recoveries. Temporal characteristics of the feet kinematics did not differ between lateral falls and recoveries. Six of seven (86%) lateral fallers placed the trailing toe onto the contaminant at touch-down of the recovery step, and this proportion did not differ from recoveries (p = 0.438; Figure 6).

The final discriminant analysis model (p < 0.001, Wilk's lambda = 0.14) correctly classified 62 of 71 slips (4 recoveries and 5 falls were misclassified). Variables significant in the final model were: peak AP slip speed, trailing toe AP position at touch-down, slipping heel AP position at touch-down, heel-to-heel AP distance at touch-down, mean trailing toe AP speed during 50 ms following touch-down and mean trailing toe ML speed during 50 ms following touch-down. These variables significantly affected the odds ratio for experiencing each type of fall (Table 2).

Discussion

This study (1) investigated differences in feet kinematics between recoveries and feet-split falls, feet-forward falls and lateral falls, and (2) identified characteristics of the slipping and trailing feet kinematics that discriminated between these four slip outcomes. Our first hypothesis was that the feet kinematics upon slipping would differ between recoveries and three types of falls. This hypothesis was supported, given the numerous differences in feet kinematics between recoveries and feet-split falls, feet-forward falls and lateral falls. In particular, feet-split falls were primarily characterised by a large heel-to-heel distance at touch-down, a more anterior slipping heel position at lift-off and touch-down, a more posterior trailing toe position at touch-down, and a slower trailing toe speed following touch-down. Feet-forward falls were primarily characterised by a more anterior slipping heel position at touch-down, and a faster anterior trailing toe speed following touch-down. Lateral falls were primarily characterised by a larger heel-to-heel AP distance at touch-down, a more anterior slipping heel position at touch-down, a more posterior trailing toe position at touch-down, and a faster mediolateral trailing toe speed following touch-down. Our second hypothesis was that modifiable, performance-related feet kinematics would discriminate between the four outcomes. This hypothesis was also supported, given that the discriminant model correctly predicted 87% of slip outcomes, and included five variables describing kinematics of the recovery response at or soon after touch-down. To our knowledge, this is the first study to report on the importance of the trailing limb response during recovery from an unconstrained slip. We also identified seemingly modifiable characteristics of feet kinematics upon slipping associated with successful slip recoveries that can serve as 'targets' for training to improve the effectiveness of slip responses. This is also the first study, again to our knowledge, to report that placing the trailing foot on a slipping contaminant after the recovery step has little influence on slip outcome.

AP placement of the trailing foot appears to be an important factor affecting slip outcome. Specifically, this placement re-establishes the base of support after a slip and provides lower limb support to arrest downward motion of the body during slip recovery. Previous studies have highlighted the importance of limb support during slip recovery (Yang, Bhatt, and Pai 2011), and deficient trailing limb support has been identified as a factor leading to slip-induced falls amongst older adults during a sit-to-stand task (Pai et al. 2006; Pavol and Pai 2007). During recoveries here, the trailing toe AP position at touch-down was 5.0 (5.9) %bh (mean (SD)) anterior to the sacrum. From the logistic model, placing the trailing toe more posteriorly increased the likelihood of a feet-split or lateral fall, possibly by diminishing the ability to provide sufficient trailing limb support. Conversely, placing the trailing toe more anteriorly increased the likelihood of a feet-forward fall. These results agree with a previous study by Yang et al. (2012), who reported feet-split and feet-forward falls resulting from slips on a sliding platform. In their study, feet-forward falls exhibited longer recovery steps with a less-posterior landing position compared to feet-split falls (Yang et al. 2012). The majority of subjects who recovered balance here (62%) placed the trailing toe within a range of 0–10%bh anterior to the sacrum (Figure 6). While 38% of recoveries occurred with trailing toe placement outside of this range, 75% of feet-split fallers, 72% of feet-forward fallers and 71% of lateral fallers placed the trailing toe outside of this range. Some falls that occurred within this range appear to have resulted from a more severe slip, anterior slipping heel position at touch-down, or large heel-to-heel distance at touch-down. Although slip outcome cannot be predicted solely by trailing toe AP position at touch-down, our results suggest it has an important influence on slip outcome, and placing the trailing foot within a general range of 0–10%bh anterior to the sacrum appears to be desirable for recovery.

Slipping heel AP position during the slip was also found to be an important factor affecting slip outcome, which agrees with previous findings (Bhatt, Wening, and Pai 2006; Troy et al. 2008; Yang, Anderson, and Pai 2008; You et al. 2001). In fact, our results (Table 2) indicate it to be the most influential variable regarding kinematics of the feet included in our final discriminate model, with odds ratios ranging from 1.22 to 2.13 between each of the three falls and recoveries. For recoveries, slipping heel AP position was 17.2 (2.4) %bh anterior at lift-off and 16.5 (5.3) %bh anterior at touch-down relative to the sacrum. Slipping heel AP position at touch-down was more anterior to the sacrum for all three fall types compared to recoveries. A more anterior slipping heel position at lift-off and touch-down might be evidence of an inappropriate or insufficient recovery response of the slipping limb. Muscle coordination in the slipping limb differs between falls and recoveries following laboratory-induced slips, since falls are associated with recruitment of fewer muscle synergies, delayed knee flexor and extensor onset times, and reduced knee and hip extensor work (Pai et al. 2006; Qu, Hu, and Lew 2012; Sawers et al. 2017). Therefore, maintaining a slipping heel position proximal (less anterior) to the sacrum appears to be important for preventing slip-related falls.

Heel-to-heel AP distance at touch-down was also an important factor affecting slip outcome, and was one of five variables identified by the stepwise discriminant analysis. This distance, however, is closely related to the AP position of the trailing toe and slipping heel at touch-down discussed above. Moreover, interventions to elicit beneficial changes in AP position of the trailing toe and slipping heel at touch-down would also result in beneficial changes in heel-to-heel AP distance. For simplicity, it may thus be easier to focus on identifying and promoting beneficial responses of individual lower limbs, rather than responses involving both limbs, during training.

Contrary to our expectations, placing the trailing toe onto the contaminated surface at touch-down did not, by itself, increase the likelihood of falling. During 95% of recoveries, the trailing toe was placed on the contaminated surface at touch-down, leading to the trailing toe slipping anteriorly at a speed of 2.45 (1.10) m/s and slipping in the mediolateral direction at a speed of 0.32 (0.27) m/s. All feet-forward fallers and all-but-one lateral faller placed the trailing toe on the contaminant at touch-down, while less than half of feet-split fallers placed the trailing toe onto the contaminant at touch-down. Interestingly, the AP distance travelled by the trailing to from lift-off to touch-down did not differ between subjects placing the trailing toe onto or off of the contaminant ($p = 0.207$ using a paired *t*-test). Placing the trailing toe *off* the contaminant arrested the speed of the trailing toe following touch-down; this placement does not seem favourable for recovery, because a slower trailing toe AP speed after touch-down increased the likelihood of a feet-split fall. In fact, trailing toe ML and AP speed over the 50 ms after touch-down were both significant predictors of slip outcome in our final discriminant model. This agrees with previous reports that slips with only one foot slipping forward are more likely to result in feet-split falls (Wang et al. 2017; Yang et al. 2012). Given that the trailing foot was placed onto the contaminant during 95% of recoveries, placing the trailing toe off the contaminant does not appear favourable for promoting recovery following a slip. Instead, it appears more important to place trailing toe within or near the 0–10%bh anterior from sacrum, even if on a contaminant, than to avoid the contaminant and place the trailing toe outside of a desirable range.

Interestingly, the time to initiate the recovery step was longer for recoveries compared to falls, and the time to complete the recovery step did not differ between recoveries and the three fall types. The time from heel contact to lift-off was 0.14 (0.02) s for recoveries, compared to 0.12 (0.02) s across all three types of falls, which agrees with a previous finding that double support time after slip onset was prolonged for subjects who successfully recover their balance following slips (You et al. 2001). As described by You et al. (2001), subjects who recover their balance may spend more time in this first double support phase from heel contact to lift-off to take advantage of the frictional control generated by the trailing leg. In terms of the time to complete the recovery step, it is tempting to speculate that a faster execution of the recovery step would be associated with recoveries. However, the time from heel contact to touch-down, and from lift-off to touch-down did not differ between slip outcomes. Similar results were reported by Troy et al. (2008) who identified risk-factors associated with slip-related falls and also found that rapidly lowering the trailing foot to the ground (i.e. time from slip onset to touch-down) did not contribute to avoiding a slip-induced fall. Conversely, Yang et al. (2012) reported that feet-split falls exhibit a longer time from heel contact to lift-off and a shorter time from lift-off to touch-down compared to feet-forward falls. Moyer, Redfern, and Cham (2009) reported that a shorter time from lift-off to touch-down was associated with more severe slips (and thus slips more likely to result in a fall (Brady et al. 2000)). Our results did not exhibit these same differences, and in absence of any other plausible explanation may have resulted from differences in experimental conditions, subject demographics or methods used to determine lift-off and touch-down times. Based on our findings, a prolonged time to initiate the recovery step – rather than a rapid time to execute the recovery step – may be advantageous for recovery from a slip.

Gait characteristics and slip severity also differed between slip outcomes. Feet-split and lateral fallers had faster walking speeds, and all three fall types exhibited longer steps during gait, compared to recoveries. This outcome is supported by previous literature in that slip-fallers walk faster and with longer steps compared to non-fallers, and that pre-perturbation gait speed and step length can influence the recovery step (Brady et al. 2000; Espy et al. 2010). However, recoveries occurred here for gait speeds as fast as 1.54 m/s and step lengths as long as 81.7 cm, and falls occurred for gait speeds as slow as 1.15 m/s and step lengths as short as 61.6 cm. Similarly, peak AP slip speed and AP slip distance were faster and farther for all three fall types compared to recoveries, and peak ML slip speed and ML slip distance were faster and farther for lateral falls compared to recoveries. Although, in general, falls resulted from more severe slips, recoveries were achieved for peak AP slip speeds as fast as 2.62 m/s and AP slip distances as long as 43 cm. Falls occurred at peak AP slip speeds as slow as 1.29 m/s and AP slip distances as short as 21 cm. Although gait characteristics and slip severity did differ between slip outcomes, slip outcome cannot be explained by these variables alone, thus highlighting the importance of the recovery response to a slip.

Several limitations were present in this study. First, all subjects were aware of the possibility of slipping or tripping. It is possible that subjects adopted a more cautious gait pattern in anticipation of a slip or trip, although subjects were instructed to walk naturally (Cham and Redfern 2002). Second, kinematic measures may have been influenced by the presence of the harness during the recovery response, although this limitation is common in slip recovery studies that use a harness. Third, we included only healthy young and middle-aged adults, and it is unclear how these results can be generalised to other populations. Fourth, our results may be dependent on the selection of contaminant and shoes to induce slips, and differences in experimental conditions could explain some differences between our results and results from others.

In summary, three general findings emerged. First, two potentially modifiable characteristics of the reactive slip response that can improve the likelihood of successfully recovering balance and averting a fall are: (1) quickly arresting the motion of the slipping foot; and (2) a recovery step that places the trailing toe approximately 0–10%bh anterior to the sacrum. Second, placing the trailing foot onto a contaminant after stepping did not adversely influence the likelihood of falling. Third, shortening the timing of the stepping response did not appear to be of major importance for improving slip recovery. These results contribute to an improved understanding of the relationship between the reactive response and the outcome of a slip, and may also inform the development of more effective task-specific balance training interventions that promote favourable reactive responses to slipping. Such fall prevention interventions have shown the potential to promote beneficial changes in reactive balance responses amongs older adults (Liu and Kim 2012; Pai and Bhatt 2007; Parijat and Lockhart 2012; Pavol, Runtz, and Pai 2004), but have receive little attention for preventing falls in the workplace.

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