Unconstrained slip mechanics and stepping reactions depend on slip onset timing

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Abstract

Slips can occur at any time during stance. Accordingly, time-dependent tangential ground reaction forces likely produce a diverse range of slipping foot mechanics when traction is lost, thus requiring flexible recovery strategies to prevent falls. However, previous research has focused on slip onset in early stance, often with experimental anteroposterior constraints on the slipping foot, despite the diversity of environmental slips and falls. This study aimed to determine the effects of slip onset time on slip direction, severity (distance and velocity), and compensatory stepping responses. Ten young adults received slipping perturbations at different times during the stance phase of walking via a wearable device that reduces available friction while allowing the slipping foot to slide freely within the horizontal plane. Slip direction, distance, and peak velocity, compensatory step direction and distance, and upper body angular momentum magnitude and plane of rotation were derived from kinematic data. All outcome measurements significantly correlated with the time of slip onset. Slip direction and the plane of rotation of angular momentum deviated widely from the sagittal plane, exhibiting laterally-directed components exceeding those in the anteroposterior direction. As slip onset occurred later in stance, slip severity decreased while compensatory steps became longer and progressed from a posterior to anterior placement. These results provide insight into critical times within stance when slips are most severe, and into the diversity of slipping mechanics caused by changes in slip onset time.

Keywords
Falls; Gait; Balance recovery; Stability; Angular momentum

1. Introduction

Extrinsic disturbances during walking, such as slips, are responsible for over half of all falls experienced by community-dwelling older adults (Berg et al., 1997; Crenshaw et al., 2017), making them a worthwhile target for fall prevention. Even a small reduction in slip-related falls would drastically reduce their impact on public health (Grabiner et al., 2014).
Substantial research has been devoted to understanding the characteristics of slips, the mechanisms for maintaining stability after they occur, and whether these mechanisms can be enhanced with training. Slip recovery thresholds of 10 cm and 50 cm/s are widely cited for the slipping foot’s displacement and velocity, respectively (Strandberg and Lanshammar, 1981), however subsequent work has shown recovery at greater magnitudes (Brady et al., 2000). Slips also cause destabilizing angular momentum that must be countered through reactive movements to prevent a fall (Mathiyakom and McNitt-Gray, 2008). One such movement is a compensatory step (CS) taken with the non-slipping leg, which enables an opposing impulse to more effectively counteract the destabilizing angular momentum (Mathiyakom and McNitt-Gray, 2008). Fallers and non-fallers utilize different CS strategies, with the former opting for shorter medial steps while the latter uses longer, more effective cross-over steps after lateral balance disturbances (Bair et al., 2016). Repeated exposure to CS-inducing perturbations improves stepping ability in older adults, characterized by faster reaction times, longer step lengths, and fewer steps taken to recover balance (Dijkstra et al., 2015; Kurz et al., 2016; Mansfield et al., 2010; Patel and Bhatt, 2015). Similarly, slip-specific balance training causes lasting stability improvements in young and older adults that generalize to realistic lab-based slips (Bhatt et al., 2006a; Bhatt et al., 2006b; Bhatt et al., 2012; Epro et al., 2018; Pai et al., 2010; Pai et al., 2014a). Altogether, these findings provide mechanical and behavioral targets for slip and fall prevention, but more work is required to determine if the protective benefits of slip-specific training seen in the lab translate to the community (Pai et al., 2014b).

While these results shape our understanding of slip recovery, the perturbations delivered within and across these studies were largely homogeneous: they occurred during quiet standing or early in stance phase, were mechanically constrained by treadmill belts or sliding platforms to move in the same direction with every repetition, and were often fixed in magnitude. In contrast, real-world walking surfaces do not restrict a slipping foot’s direction and therefore elicit unconstrained slips. Accordingly, studies using slippery walking surfaces are exceptions to the previous constraints, as the unconstrained slips they cause move in oblique directions and show greater kinematic variability than constrained slips administered via sliding platform (Troy and Grabiner, 2006). The location of a slippery surface in the lab is predictable after first exposure, however, leading to unnatural anticipatory effects (Bohm et al., 2015; McCrum et al., 2017; Pater et al., 2015). From a specificity of training perspective, a narrow range of delivered gait perturbations (i.e. only anterior slips) reinforces an equally narrow range of recovery strategies that may not be effective against the entire range of possible disturbances. For example, posteriorly directed slips generally place forward pitching angular momentum on the upper body (Pijnappels et al., 2004; Pijnappels et al., 2005) while anteriorly directed slips cause the opposite (Gu et al., 1996), indicating that the destabilizing effects to be countered are direction-dependent. Alternatively, exposing individuals to a diverse range of realistic, unconstrained slips may enhance their recovery abilities beyond what has been demonstrated (Grabiner et al., 2008).

As one progresses through stance, their ground reaction forces (GRFs) and body configurations are constantly changing, creating a unique set of initial conditions at every instant on which a slip can act and a reaction must begin. The slip mechanics that arise, such as the direction, distance, and velocity of the slipping foot and the destabilizing angular
momentum that results, may therefore depend on the timing of the slip during stance. Similarly, possible CS placements could be determined by initial conditions present at slip onset and therefore may also depend on slip onset timing. Preliminary data from the validation of a new slip perturbation device are consistent with these hypotheses (Rasmussen and Hunt, 2019). Slip onset timing during stance has not been experimentally controlled in previous studies, therefore it is unclear if it influences slip mechanics. Further, the impact that it has on the body’s angular momentum and subsequent CS reactions is unknown.

Our aim was to assess the influence of slip onset timing on slip mechanics and CS reactions. The Wearable Apparatus for Slip Perturbations (WASP) was used to administer unconstrained slips at different stance phases (Rasmussen and Hunt, 2019). We hypothesized that manipulating slip onset time would change slip distances, directions, and velocities. Furthermore, we hypothesized that manipulating slip onset time would affect upper body angular momentum magnitudes and planes of rotation. Finally, we hypothesized that manipulating slip onset time would modify CS distances and directions.

2. Methods

2.1. Study participants

Ten healthy, young adults (mean ± SD age: 25.4 ± 3.4 years, height: 1.75 ± 0.07 m, weight: 80.7 ± 14.5 kg, 2 females) were consented to participate in this study, which was reviewed and approved by the University of Nebraska Medical Center Internal Review Board. Exclusionary criteria included cardiopulmonary, musculoskeletal, and neurological conditions that may have influenced normal gait patterns; pregnancy, and history of back or lower extremity injury and/or surgery. Height and weight were recorded from each subject.

2.2. Experimental set-up and protocol

All subjects wore a compression suit, standardized athletic shoes, a fall-arresting safety harness, and a WASP device (Fig. 1A) on each foot. The design and function of WASP have been detailed elsewhere (Rasmussen and Hunt, 2019). Briefly, WASP provides sufficient friction with the ground for the wearer to walk naturally until remotely triggered by an attending researcher, which suddenly reduces friction by exposing the wearer to a lubricated surface on the outsole. An advantage of this device is that it delivers unconstrained slip perturbations, where the slipped foot can move and rotate freely (Fig. 1C). A full-body marker set was tracked with a 17-camera motion capture system (Motion Analysis Corp.; Santa Rosa, CA) at 120 Hz, while the friction reduction time (i.e. WASP outsole detachment) was recorded in synchrony via Bluetooth receiver. A load cell (HT Sensor Technology Co. LTD; Xi’an, China) in series with the safety harness quantified the support provided to the wearer during every trial. If a force exceeding 30% of the subject’s body weight was detected, the trial was classified as a fall (Yang and Pai, 2012). Any trial not meeting this criterion was deemed a recovery.

Subjects walked back-and-forth across an eight meter walkway and were told that they “may or may not experience a slip” (Pai et al., 2014). After a random duration between one and four minutes, a slip was delivered that visually targeted early stance (0–33% of stance...
phase), mid-stance (34–67%), or late stance (68–100%) to obtain a broad range of slip onset times (Fig. 1B). A seated rest period followed every trial, during which the triggered WASP outsole was reattached. All subjects performed 12 trials, all of which included a slip. Trial duration, friction reduction time, and targeted foot were randomized via MATLAB script (Mathworks, Inc.; Natick, MA).

2.3. Data analysis

The following analysis was conducted in Visual3D (C-Motion, Inc.; Germantown, MD). A fourth-order low-pass Butterworth filter with a 6 Hz cutoff frequency was applied to all marker trajectories. Gait events were determined using a coordinate-based algorithm (Zeni et al., 2008). The friction reduction time often did not align with the instant that the targeted foot began to slide. Therefore, the moment that the targeted foot’s horizontal velocity began to increase following outsole release was considered the slip onset time. Similarly, slip cessation time was either the instant that the horizontal velocity returned to zero or the following push-off (i.e. for late stance slips, because sliding never ceased before push-off). Twenty-nine trials were excluded for failed slip initiation or marker occlusion that caused the loss of a segment, leaving 91 trials for analysis.

Friction reduction time ($p_{FR}$) and slip onset time ($p_{onset}$) were taken as the percentage of stance at which WASP was activated and the foot began to slide, respectively. Slip distance ($d_{slip}$), direction relative to the subject’s heading ($\theta_{slip}$), and peak velocity ($v_{slip}$) between slip onset and cessation (Fig. 1C) were derived from foot kinematic data, while CS distances ($d_{CS}$) and directions ($\theta_{CS}$) were calculated in relation to the center of mass (CoM) at heel-strike of the non-slipping foot (i.e. CS touchdown). Upper body angular momentum magnitudes ($\parallel L \parallel$) and planes of rotation ($\theta_{LPOR}$) were obtained from the sum of trunk, upper arm, forearm, and head angular momenta about the CoM, and the value of each at CS touchdown was extracted for analysis. Definitions and equations for these outcome measures are in Table 1.

2.4. Statistical analysis

Due to non-normal and heteroscedastic data distributions, Spearman’s rank correlation coefficients were calculated between slip onset time and slip direction, distance, and peak velocity; CS distance, CS direction, and upper body angular momentum magnitude and plane of rotation at CS touchdown. The critical alpha was $\alpha = 0.05$.

3. Results

3.1. Slip onset time vs. friction reduction time

A broad, bimodal distribution of slip onset times were delivered across stance phase (Fig. 2B). Few slips occurred during mid-stance, despite the roughly uniform distribution of friction reduction times (Fig. 2A). Slip onset times rarely corresponded with friction reduction – early stance slips were often triggered at or before heel-strike, while late stance slips were triggered across stance (Fig. 2A, 2B).
3.2. Slip mechanics

The delivered unconstrained slips varied in their mechanics and exhibited significant associations with slip onset timing. A significant strong, positive correlation was found between slip onset time and slip direction ($\rho(89) = 0.659$, $p < 0.001$; Fig. 2E). Slip directions almost always possessed a degree of lateral displacement compared to the foot’s position before slip onset (Fig. 2C, 2D); the median direction was 108° (IQR: 65-141°) from the subject’s heading. Slip distances (median: 0.07 m, IQR: 0.04–0.12 m) exhibited a significant strong, inverse correlation with onset time ($\rho(89) = -0.609$, $p < 0.001$; Fig. 2F). The negative correlation observed between onset time and peak slip velocity (median: 0.63 m/s, IQR: 0.26–0.96 m/s) was weak, yet significant ($\rho(89) = -0.246$, $p = 0.019$; Fig. 2G). Together, these correlations indicate that as unconstrained slips occur later in stance, they tend to shorten, slow, and move in a progressively lateral and ultimately posterior direction. Despite the broad range of slip mechanics, no trials met the load cell-based criterion to be classified as a fall.

3.3. Upper body angular momentum

A broad range of upper body angular momenta followed slip initiation across stance phase (Fig. 3A) and also correlated significantly with slip onset time. The upper body plane of rotation at CS touchdown (median: 66°, IQR: 53-83°) revealed a significant moderate, negative association with onset time ($\rho(89) = -0.493$, $p < 0.001$). This indicates that the upper body rotates in a lateral and opposite direction to the person’s heading after early stance slips, but progresses to a primarily lateral rotation before approaching the walking direction with later onset times (Fig. 3B). A significant moderate, inverse correlation between upper body angular momentum magnitude at CS touchdown (median: 1.77 kgm$^2$/s, IQR: 1.24–2.57 kgm$^2$/s) and onset time ($\rho(89) = -0.563$, $p < 0.001$; Fig. 3C) was also found, suggesting that slip-induced angular momentum decreases with advancing onset time.

3.4. Compensatory steps

CS were highly variable in their placement relative to the CoM (Fig. 4A). The greatest variation was in the anteroposterior direction, ranging from behind the CoM to longer than the average unperturbed step. CS also always possessed a lateral component from the CoM that, although still covering a large range, varied less than the anteroposterior component. CS directions (median: 16°, IQR: 14-24°) showed a significant moderate, negative correlation with slip onset time ($\rho(89) = -0.599$, $p < 0.001$; Fig. 4B). Conversely, a significant strong, positive relationship between CS distance (median: 0.34 m, IQR: 0.29–0.38 m) and onset time was found ($\rho(89) = 0.694$, $p < 0.001$; Fig. 4C). Based on these correlations, CS lengthen with advancing onset time and are placed in a direction approaching that of travel.

4. Discussion

Unconstrained slipping disturbances with different onset times during stance elicit mechanically diverse challenges for balance recovery. Manipulating slip onset time markedly changed slip distances and directions (Fig. 2E, 2F), while peak slip velocity was weakly yet significantly correlated with onset time as well (Fig. 2G). Moreover, the
magnitude and direction of upper body angular momentum after slipping also changed with onset time (Fig. 3B, 3C). Finally, CS responses also changed with onset time (Fig. 4), suggesting that recovery reactions are tailored to the destabilizing effects of the perturbation on the body.

The multitude of slip, angular momentum, and CS directions we observed mimic real-life balance disturbances and recoveries. Indeed, community-based slips and falls are exceedingly diverse, as are the recovery reactions employed to regain stability. In a study of healthy older women, primarily forward-directed and backward-directed falls of any cause happened at similar rates (44% and 41%, respectively), and only 56% of reported slips resulted in a backward fall (Crenshaw et al., 2017). Forward falls pose a particular risk of impact to the knees, wrists, and head, while the hips and trunk are at greatest risk when falling backward (Crenshaw et al., 2017; Hsiao and Robinovitch, 1997; Schonnop et al., 2013). Recovery reactions to prevent these falls are direction-dependent, requiring different neuromuscular and multi-joint control patterns to regain balance from forward- and backward-directed perturbations (Hsiao and Robinovitch, 2001; Pijnappels et al., 2005). On the other hand, lateral falls pose the greatest risk of impact to the elbows, shoulders, and hips (Crenshaw et al., 2017; Yang et al., 2016), and a unique trunk rotation strategy toward the direction of the fall has been observed (Hsiao and Robinovitch, 1997). Little research has examined perturbations in an oblique direction, however, despite evidence here and elsewhere that unconstrained slips and falls possess sagittal and frontal plane components (Crenshaw et al., 2017; Troy and Grabiner, 2006). Consequently, it is unclear how established balance recovery strategies such as CS, trunk control, and arm swing are influenced by slip direction. Controlling the onset time of unconstrained slips provides the needed “three-dimensional” approach to examine multidirectional slip recovery.

Friction reduction times were uniformly distributed across stance (Fig. 2A), but the bimodal distribution of slip onset times showed a propensity for early and late stance slips (Fig. 2B). Braking and propelling forces peak during early and late stance, respectively, leading to large required coefficients of friction when coupled with weak concomitant vertical GRFs. Therefore, the prevalence of early and late stance slips stems from the difference between the available friction supplied by WASP after release ($\mu \approx 0.07$) (Rasmussen and Hunt, 2019) and the required friction immediately following heel-strike and preceding push-off ($\mu \approx 0.20$ and 0.28, respectively) (Beschorner et al., 2016; Redfern et al., 2001). While more mid-stance slips could be delivered by further reducing available friction, it would have to be so miniscule ($\mu \leq 0.05$) (Burnfield and Powers, 2007; Redfern et al., 2001) that it is difficult to attain with currently available low-friction materials. Therefore, we believe the distribution of slip onset times observed here is indicative of those that present the highest probability of slipping during straight, level walking. Our day-to-day gait and environment are much more complex, however, as turns (Glaister et al., 2007) and sloped surfaces are common. These conditions require greater friction to prevent a slip (Fino and Lockhart, 2014; Redfern and DiPasquale, 1997), and the increased shear GRFs (Dixon and Pearsall, 2010; Glaister et al., 2008; McIntosh et al., 2006; Orendurff et al., 2006) may increase mid-stance slip risk and alter the relationships between slip onset timing and the outcome measures examined here. Further research should extend this analysis to other gait modes and environments.
While early and late stance slips were most likely to occur, the mechanics and CS observed after they began suggest notable differences in severity. As slip onset progressed later into stance phase, the resulting slip distances, peak velocities, and upper body angular momenta tended to decrease (Fig. 2F, 2G, 3B). In general, shorter, slower slips that evoke less compromising trunk mechanics are easier to recover from, leading to a lower fall risk (Brady et al., 2000; Crenshaw et al., 2012; Strandberg and Lanshammar, 1981). However, despite 34% of our slips exceeding 10 cm and 56% surpassing 50 cm/s, we did not register a fall based on load cell readings. This aligns our findings with those of Brady and colleagues: that slip recovery is possible beyond those thresholds (Brady et al., 2000; Strandberg and Lanshammar, 1981). The lack of falls prevents us from making inferences about how slip onset time interacts with fall risk, although we hypothesize that early stance slips pose the greatest risk. In addition to being more severe, early stance slips showed greater variability in many reported measures. One explanation may be that multiple viable recovery strategies are available during early stance; “skate-over” and “walk-over” strategies, for example, have been reported in response to the same sliding platform-induced heel-strike perturbation (Bhatt et al., 2005). These alone could cause disparate slip mechanics and CS placements, as skate-over responses allow the slip to carry out before taking a forward step while walk-over responses limit slip distance and velocity with an immediate, shorter step (Bhatt et al., 2005). Because previous research has focused on early stance slips, distinct recovery strategies used to counter late stance slips have not been described. Multiple strategies may not exist or be needed, however, since the non-slipping foot is nearly or already placed at that time. Nevertheless, the focus on early stance was well-placed based on our results, as these slips are most likely to be severe and mechanically diverse.

Our results suggest another potential utility of controlling slip onset time: to deliver a diverse range of realistic perturbations in a slip-specific balance training protocol. Where repeated use of one perturbation type may strengthen only the ability to recover from that specific disturbance, administering a comprehensive range of perturbations may reinforce an equally comprehensive repertoire of recovery strategies. This “variable slip training” may benefit from contextual interference, where learning a motor task under varying conditions leads to enhanced retention, improved transfer to novel environments, and less reliance on memory (Shea and Morgan, 1979). Similar forms of perturbation training provide support for contextual interference in learning recovery skills. For example, studies that delivered opposing perturbations (i.e. anteriorly-directed slips and trips) reported generalized adaptations rather than one inhibiting the ability to recover from the other, a finding attributed to increased reliance on reactive rather than proactive stability control (Bhatt et al., 2013; Okubo et al., 2018). With more perturbation types, Takazono and colleagues demonstrated greater recovery skill retention and generalization after randomly delivered perturbations than after a blocked design (Takazono et al., 2020). Using perturbations that more closely mimic environmental slips also enhances generalization of learned recovery skills (Lee et al., 2016). Our results indicate that a range of realistic slips can be administered simply by controlling onset time, which may provide relevant contextual interference and ecological validity in a balance training protocol to maximize generalization to natural slips. Whether or not variable slip training enhances retention and transfer compared to other slip-specific methods should be investigated.

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This study has a number of limitations. First, although subjects were unaware of the specifics of each slip before it was delivered, they may have anticipated a slip during every pass across the lab, causing proactive adaptations that would not otherwise occur (Bohm et al., 2015; McCrum et al., 2017; Pater et al., 2015). Second, our data was obtained from a sample of young adults, and is therefore not representative of populations at higher fall risk. Furthermore, none of the slips caused a fall, preventing strong conclusions regarding how fall risk is influenced by onset time. While we believe the correlations between slip mechanics and slip onset time would be similar in high-risk populations, those between CS and onset time could differ due to contrasting stepping abilities between young and older adults, for example (Bair et al., 2016). Future studies should determine whether conditions that increase fall risk interact with these associations. Third, the application of our findings across sex may be limited since only 20% of our sample was female. Finally, the slip onset time determined via kinematics was often later than the friction reduction time, likely due to differences between required and available friction. This did not prevent our aims from being met but could make precise targeting of specific times or gait events difficult.

5. Conclusion

We demonstrated that diverse slip onset times cause a range of unconstrained slip perturbations and CS responses. As slips begin later in stance phase, they tend to be shorter, slower, and move from anterior to posterior; upper body angular momentum decreases and progresses from a posterior to anterior rotation, and CS lengthen and progress from a posterior to anterior placement. Because a wide array of balance disturbances can be delivered, controlling onset time may have valuable implications to the study of recovery strategies and task-specific fall prevention protocols. Our results also identify critical times when slips are most likely and most severe, providing targets for training protocols. Future research should examine recovery strategies after multidirectional slips and determine the efficacy of diverse slip training protocols.

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6. Data Availability Statement

Datasets collected and analyzed in this study are available from the corresponding author upon reasonable request.

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Fig. 1. Study Design

(A) A Wearable Apparatus for Slip Perturbations (WASP) assembled on a shod prosthetic foot to demonstrate how it interfaces with the wearer, as well as focused images of the outsole, cam-and-follower release mechanism, and 3D printed buckles on nylon straps that connect the two components. (B) An illustration of the experimental set-up and protocol utilized in this study. (C) An illustration of unconstrained slip direction ($\theta_{\text{slip}}$), distance ($d_{\text{slip}}$), and peak velocity ($v_{\text{slip}}$) used in this study.
Fig. 2. Slip Onset Timing Distribution and Mechanics

(A) A timeline of friction reduction times ($p_{FR}$) at which WASP was triggered by the researcher. Stacked points occurred at the same percentage of stance, and those at 0% $p_{FR}$ correspond to perturbations where WASP was triggered prior to or at heel-strike of the targeted foot. The color gradient corresponds with that in panel B. (B) A timeline of actual slip onset times ($p_{onset}$). In this and all figures that use the color gradient, blue corresponds to early stance slips, while red corresponds to late stance slips. (C) A polar plot showing slip direction ($\theta_{slip}$) on the t-axis and slip distance ($d_{slip}$) on the r-axis. The origin corresponds
to a slip distance of 0 m. Positive t-axis values correspond to directions lateral to the heading, while negative values are medial to the heading. (D) A polar plot illustrating $\theta_{\text{slip}}$ on the t-axis and peak slip velocity ($v_{\text{slip}}$) on the r-axis. The origin is equivalent to a slip velocity of 0 m/s. T-axis signs carry the same meaning as in Fig. 2C. (E) A scatter plot of the relationship between $p_{\text{onset}}$ and $\theta_{\text{slip}}$. Analogous to the polar plots in Fig. 2C and 2D, positive values are lateral to the heading, 0° is in perfect alignment with the heading, and negative values are medial to the heading. (F) A scatter plot of the correlation between $p_{\text{onset}}$ and $d_{\text{slip}}$. (G) A scatter plot of the association between $p_{\text{onset}}$ and $v_{\text{slip}}$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Fig. 3. Upper Body Angular Momentum

(A) Resultant, sagittal, and frontal plane upper body angular momentum traces for each slip trial from the moment of slip onset to 1 s post-onset. A projected view of $\|L\|$ versus time is also provided as an aside to better illustrate the differences in peak $\|L\|$. (B) A scatter plot displaying the correlation between $p_{\text{onset}}$ and the direction of the angular momentum plane of rotation ($\theta_{\text{POR}}$). Smaller values indicate a direction closer to that of walking, while larger values are approaching the opposite direction to that of walking. (C) A scatter plot relating
slip onset time ($p_{onset}$) with the magnitude of resultant upper body angular momentum experienced at the instant of CS touchdown ($||L||$).
Fig. 4. Compensatory Step (CS) Reactions
A) A scatter plot presenting the locations of CS relative to the location of the whole-body CoM, color-coded by onset time ($p_{onset}$). The average (±1 SD) placement of unperturbed steps is represented by a black diamond and error bars. B) A scatter plot exhibiting the relationship between $p_{onset}$ and CS direction ($\theta_{CS}$). Larger positive values are approaching the opposite direction of travel, while smaller values are approaching the direction of travel. The average ± 1 SD direction of unperturbed steps is indicated by a dashed line and shaded area. C) A scatter plot showing the association between $p_{onset}$ and CS distance ($d_{CS}$). The average ±1 SD distance of unperturbed steps is represented by a dashed line and shaded area.
Table 1

Explanations of the reported variables and how they were derived, as well as intermediate factors needed to obtain these variables. Outcome measures reported in the results are bolded. Other variables listed were used to calculate the outcome measures. Note: the segments (s) used to calculate upper body angular momentum were the trunk, upper arms, forearms, and head.

| Symbol | Description | Calculation | Units |
|--------|-------------|-------------|-------|
| $t_{fr}$ | time between the WASP triggering and the heel-strike event of the targeted stance phase | measured | s |
| $t_{onset}$ | time between slip onset and the previous heel-strike of the slipping foot | measured | s |
| $t_{stance}$ | duration of the stance phase during which the slip occurred | measured | s |
| $p_{stance}$ | Slip Onset Time: percentage of stance phase at which the slip began | $p_{onset} = t_{onset} / t_{stance}$ | % stance |
| $p_{fr}$ | Friction Reduction Time: percentage of stance phase at which friction underfoot was reduced by triggering WASP | $p_{fr} = t_{fr} / t_{stance}$ | % stance |
| $t_{stop}$ | time at which the slipping foot stopped sliding | measured | s |
| $\text{CoM}_{\text{foot}}$ | location of the slipping foot’s CoM in the horizontal plane | measured | m |
| $d_{slip}$ | Slip Distance: displacement between the slipping foot’s CoM at slip onset and slip cessation in the horizontal plane | $d_{slip} = \sqrt{\left(\text{CoM}_{\text{foot}}(t_{onset}) - \text{CoM}_{\text{foot}}(t_{stop})\right)^2}$ | m |
| $\theta_{slip}$ | Slip Direction: angle between the slipping foot’s displacement vector and the subject’s heading in the horizontal plane | $\theta_{slip} = \sin^{-1}\left(\frac{X_{d_{slip}}}{d_{slip}}\right)$ | deg. (°) |
| $v_{slip}$ | Peak Slip Velocity: maximum velocity attained by the slipping foot’s CoM during the slip | $v_{slip} = \max\left(\Delta\text{CoM}_{\text{foot}} / \Delta t\right)$ | ms$^{-1}$ |
| $t_{cs}$ | time that the compensatory step with the non-slipping foot was placed (i.e. heel-strike) | measured | s |
| $\text{CoM}_{\text{body}}$ | location of the whole-body CoM in the horizontal plane | measured | m |
| $\text{CoM}_{\text{footCS}}$ | location of the non-slipping foot segment’s CoM in the horizontal plane | measured | m |
| $d_{cs}$ | Compensatory Step Distance: difference in position of the whole-body CoM and the non-slipping foot segment’s CoM at heel-strike in the horizontal plane | $d_{cs} = \sqrt{\left(\text{CoM}_{\text{foot}}(t_{CS}) - \text{CoM}_{\text{body}}(t_{CS})\right)^2}$ | m |
| $\theta_{cs}$ | Compensatory Step Direction: angle between the line connecting the whole-body CoM and non-slipping foot segment’s CoM at heel-strike and the subject’s heading in the horizontal plane | $\theta_{cs} = \sin^{-1}\left(\frac{X_{d_{cs}}}{d_{cs}}\right)$ | deg. (°) |
| $L$ | Upper Body Angular Momentum Magnitude: magnitude of the upper body angular momentum about the whole-body CoM at the moment of compensatory step heel-strike | $\|L\| = \|\sum_{s=1}^{S}(I_s\omega_s + r_s \times m_s v_s)\|$ | kgm²s$^{-1}$ |
| $\theta_{L}$ | angle between the upper body angular momentum vector and the subject’s heading in the horizontal plane | $\theta_{L} = \sin^{-1}\left(\frac{\|L\|}{\|L\|}\right)$ | deg. (°) |
| Symbol | Description                                                                 | Calculation       | Units   |
|--------|-----------------------------------------------------------------------------|-------------------|---------|
| $\theta_{L}^{\text{PoR}}$ | Upper Body Angular Momentum Plane of Rotation: angle between the plane within which the upper body is rotating and the subject’s heading | $\theta_{L}^{\text{PoR}} = \theta_{L} + 90$ | deg. (°) |