Characterizing slip-like responses during gait using an entire support surface perturbation: Comparisons to previously established slip methods

Andrew H. Huntley[a],[*], Roshanth Rajachandrakumar[a], Alison Schinkel-Ivy[b], Avril Mansfield[a],[c],[d]

[a] Toronto Rehabilitation Institute–University Health Network, 550 University Ave, Toronto, Ontario, M5G 2A2, Canada
[b] School of Physical and Health Education, Nipissing University, 100 College Drive, North Bay, Ontario, P1B 8L7, Canada
[c] Evaluative Clinical Sciences, Hurvitz Brain Sciences Research Program, Sunnybrook Research Institute, 2075 Bayview Ave, Toronto, Ontario, M4N 3M5, Canada
[d] Department of Physical Therapy, University of Toronto, 500 University Ave, Toronto, Ontario, M5G 1V7, Canada

ABSTRACT

Background: The characteristics of experimentally induced slips (low-friction surfaces and non-motorized platforms) in laboratory settings are influenced by participant gait velocity, contact surface area, and level of friction between the foot and surface. However, motorized platforms that could account for these factors during slip-like paradigms have not been extensively used.

Research question: How does slip-like perturbations evoked via a motorized platform change gait characteristics and postural stability during overground walking?

Methods: Ten healthy young adults performed 4 overground, self-paced walking trials, with the 4th trial including an unexpected forward support surface translation at heel-strike during steady state walking. Kinematic and kinetic data were collected, with step characteristics (time, distance, velocity) and postural stability calculated to compare between normal gait and slip-like trials. Slip foot characteristics were also determined.

Results: Peak slipping foot velocity variability was considerably smaller compared to previously reported low-friction and non-motorized perturbations. The centre of mass was shifted more posteriorly (thus in a less stable location) by the end of the platform acceleration phase compared to the same time point post-heel strike during normal gait trials. Participants successfully responded to every slip-like perturbation by significantly increasing step time, decreasing step distance, and decreasing step velocity.

Significance: Our results demonstrate the repeatability and consistency of a motorized support surface paradigm to induce slip-like perturbations. Furthermore, stability and step characteristic results confirm posterior shifts in stability and appropriate stepping responses, mimicking how participants would react if responding to a real world slip.

1. Introduction

Falls occur most frequently during overground walking [1]; approximately 1 in 4 falls are due to a slip [2]. Slips that lead to falls typically occur when the frictional force opposing the base of support (e.g. lead foot) during gait is less than the shear force of the lead foot immediately after heel contact [3]. Backward-directed falls, which often occur after slips, pose a great risk of injury due to a high prevalence of hip and pelvis impacts [2]. Fall-related injuries such as hip fractures pose a significant threat to older adults' health and well-being [4].

Due to these health risks associated with falls, and in particular slips, multiple studies have investigated the mechanics of slips in laboratory settings. Researchers commonly use low friction surfaces or

non-mechanized movable platforms to induce unexpected slips during walking [5,6]. Low friction surfaces involve placing a clear liquid solution on the support surface without participants' knowledge [5,7]. Non-mechanized movable platforms slide forward at heel contact to induce a slip [8]. Both of these modalities have been compared, demonstrating similar slipping limb velocity and slipping limb peak shear force [5].

While low friction surfaces and non-mechanized movable platforms have been commonly used, they have a number of limitations that can influence slip magnitude. Heel contact velocity (and, by extension, gait velocity) directly influences frictional demands due to its proportional relationship to horizontal shear force [3,9]. Differences in gait velocities can complicate comparisons between individual participants or groups as the slip perturbation magnitude will depend on gait velocity.

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* Corresponding author at: Room 11–107, Toronto Rehabilitation Institute, University Health Network, 550 University Ave, Toronto, Ontario, M5G 2A2, Canada.
E-mail address: andrew.huntley@uhn.ca (A.H. Huntley).

Additionally, differences in surface friction due to the application of low-friction surface solutions within or across studies can limit the ability to compare results. Ultimately, characteristics that can introduce slip perturbation variability may unknowingly affect outcomes.

A mechanized support surface may also be used to induce slip-like responses during overground walking [10,11]. In this case, a consistent and repeatable forward movement of the entire support surface can be initiated at lead heel contact. However, because the platform moves both the slipping and trailing limbs in contact with the surface, the mechanical effects may not be equivalent to a 'true' slip, where only one limb moves unexpectedly. This study aimed to investigate the potential to use a moving platform to evoke slip-like responses among healthy young adults. Specifically, we characterized the effects and responses to sudden acceleration of the platform, triggered by heel contact during overground walking, and compared these responses to those reported in previous studies using low friction surfaces and non-mechanized moveable platforms. We hypothesized that variability in slipping foot characteristics would be smaller with the mechanized platform perturbation compared to previous studies using non-mechanized slip perturbation modalities. Furthermore, we hypothesized that the platform perturbation would induce backward movements of the COM (compared to normal, overground walking) similar to previous slip perturbation studies that would require participants to appropriately react to maintain balance and avoid a fall.

2. Methods

2.1. Participants

Participants were recruited as part of another study [12]. Ten healthy young adults (6 women and 4 men; mean ± standard deviation, age: 27.3 ± 4.1years, height: 169 ± 10 cm, weight: 68.5 ± 10.3 kg) were included in the current analysis. Eligible participants could not have musculoskeletal, neurological, cardiovascular and/or visual conditions that can affect balance. Participants were excluded if they had previously participated in studies with a moving platform. This study was approved by the institution's Research Ethics Board, and participants provided written informed consent.

2.2. Experimental protocol & data capture

All trials were performed along a 6 m walkway atop a motion platform that can be programmed to translate in both the anteroposterior and mediolateral directions [13]. Kinetic data were captured via four force platforms embedded in the walkway (AMTI, Watertown, MA, USA) at 250 Hz while kinematic data were collected via a 13-camera Vicon motion capture system (Vicon MX40 +, Vicon Motion Capture Systems Ltd., Oxford, UK) at 100 Hz. Participants were outfitted with 23 single reflective markers on the following anatomical landmarks: four markers on a headband placed on the cranium (positioned so markers were bilateral, front and back head), acromioclavicular processes, lateral elbows, ulnar styloid processes, xyphoid process, iliac crests, anterior and posterior superior iliac spines, greater trochanters, lateral epicondyle of the knee, and lateral malleoli. Four additional markers, on the heels and 2nd metatarsal joints, were used to track specific gait events (e.g. heel strike, toe off), and to determine the stability boundaries in the posterior direction. Kinetic and kinematic data were synchronized during processing using optical light triggers placed on the motion platform.

Participants first completed perturbations to stance that are not reported here [12]. Participants then performed 3 overground gait trials (GAIT) followed by 1 overground perturbation trial (PERT) while wearing everyday walking shoes (see Fig. 1A). Participants wore a safety harness attached to an overhead support during all trials. Participants were instructed to walk at their self-selected speed from one end of the walkway to the other. To induce an unexpected slip-like

perturbation, participants were told that the platform would not move in any of these trials. Platform movement was triggered on the 4th trial when the vertical force at heel strike was greater than 50 N [14]. The perturbation waveform consisted of a square wave with 300 ms acceleration followed by 300 ms deceleration (peak acceleration: 1.5 m/s², peak velocity: 0.45 m/s, total displacement: 0.135 m) [15]. While there was no delay programmed between step trigger and platform motion, due to inertia, it took approximately 30 ms after the trigger for the platform to reach an acceleration of at least 0.1 m/s² (as evident in Fig. 1B).

2.3. Data processing

Kinematic data were labelled using Vicon Nexus software (Vicon Nexus v.1.8.5, Vicon Motion Capture Systems Ltd., Oxford, UK), and analyzed in Visual 3D v.5 (C-Motion, Germantown, USA). All kinematic data were interpolated, and subsequently low pass filtered at 6 Hz using a 4th order dual-pass Butterworth filter. Whole-body COM was calculated based on a modified 13 segment Winter model [16] with the following segments: head, upper arms, lower arms, upper trunk, middle trunk, lower trunk, pelvis, upper legs, and lower legs. Kinetic data were also analyzed in Visual 3D; kinetic data were downsampled to 100 Hz to match the kinematic data, and were then filtered similarly to kinematic data. The same threshold level for platform perturbation triggering (50 N) was used to determine foot contact (slip foot contact; SlipCon), contralateral foot liftoff (recovery foot liftoff; RecLift), and contralateral foot contact (recovery foot contact; RecCon). While no perturbation occurred during the GAIT trial, foot contact, contralateral foot liftoff, and contralateral foot contact were still defined and named similarly as the PERT trial to allow comparison of time points. The time point at the end of the acceleration period (EAP) of the perturbation, which occurred 300 ms following perturbation onset, was also determined (see Fig. 1B).

The stability measure was calculated using methods described in previous slip-perturbation studies [5,17]. In brief, COM position in the anteroposterior direction was expressed relative to the posterior boundary of the foot (heel marker) and was then normalized to participant's foot length (anteroposterior distance between the heel and 2nd metatarsal markers). COM velocity in the anteroposterior direction was expressed relative to the velocity of the posterior boundary of the foot, and then normalized as a dimensionless fraction $(g \times h)^{0.5}$ [5,17,18], where g is acceleration due to gravity and h is participant height. COM velocity was plotted against COM position (see Fig. 2), and stability was defined as the perpendicular distance between the COM position − COM velocity curve and the posterior predicted boundary at the previously mentioned gait events (stability at SlipCon, RecLift, and EAP). The predicted boundaries of stability were adapted from Patton et al. [17]. Stability was not computed at RecCon, as the platform deceleration would assist participants in regaining balance, and thus not merely represent participants' responses to the perturbation.

In addition to stability analyses, gait characteristics were calculated: step distance was computed as the anteroposterior distance between heel markers from SlipCon to RecCon; step time was the time between SlipCon and RecCon; and step velocity was step distance divided by step time. Lastly, slipping foot characteristics were determined as previously reported [5]. In brief, these included peak foot velocity (obtained from the heel marker of the slipping limb from SlipCon to RecLift), peak slip shear force (obtained from anteroposterior shear force of slipping limb from SlipCon to RecLift; normalized to body weight), and peak coefficient of friction from SlipCon to RecCon (determined as the ratio of the anteroposterior shear force to vertical force).

2.4. Statistical analyses

Statistical analyses were conducted using SAS 9.2 (SAS Institute, NC, USA). Participants walked progressively faster from GAIT trials
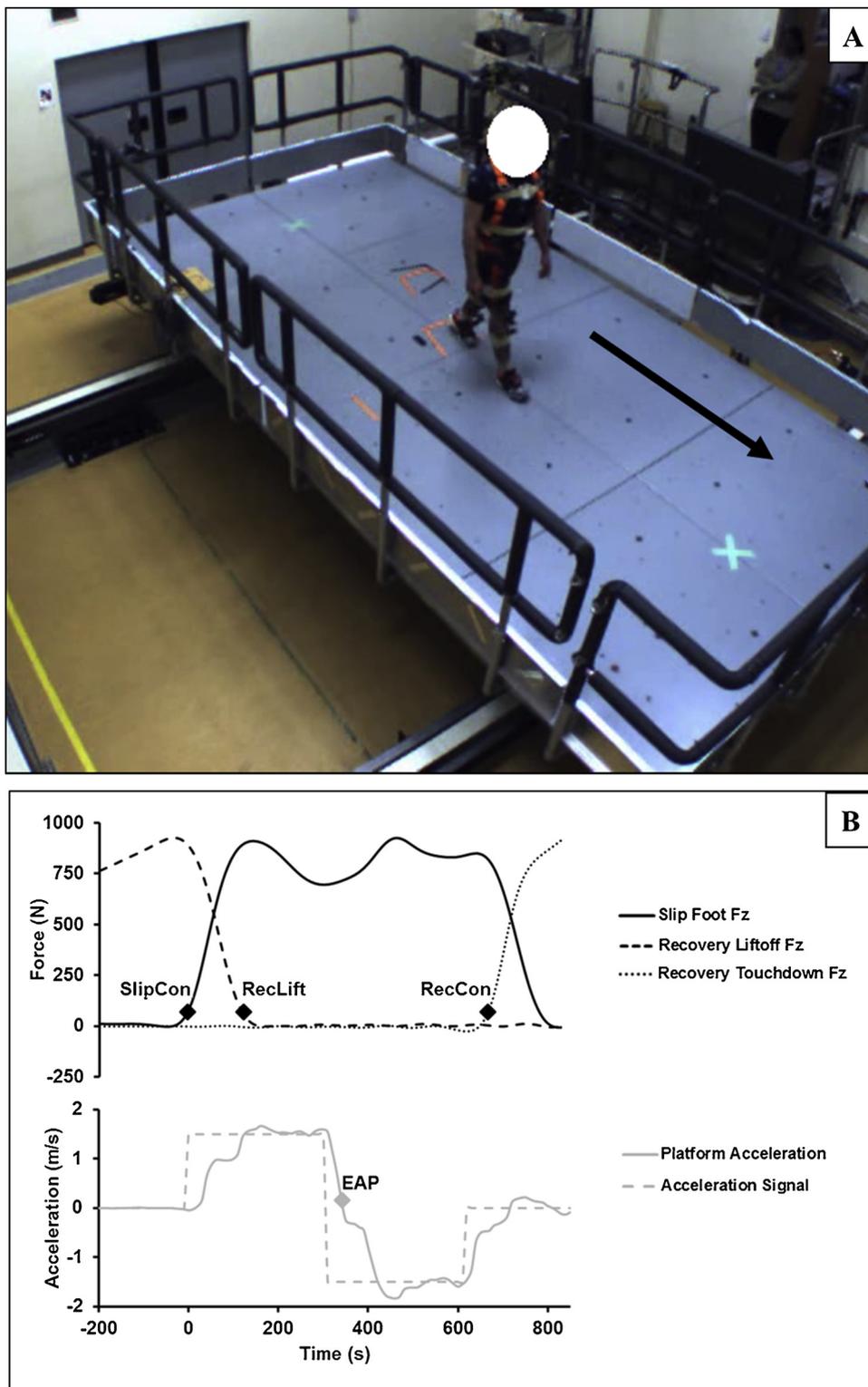
Fig. 1. A) A screen capture showing one participant walking across the platform, with their slipping limb striking the force platform monitoring heel strike (50N threshold) to trigger a slip- like perturbation. The black arrow represents the direction of platform movement. B) A representative plot of the slip foot contact vertical force (Fz; black line), recovery foot liftoff Fz (black dash line), and recovery foot contact Fz (black dot line); and the platform acceleration (secondary axis, grey solid line) and signal acceleration (secondary axis, grey dash line). The platform acceleration profile was consistent trial-to-trial. Specific events are denoted in black diamonds (slip limb contact: SlipCon, recovery limb liftoff: RecLift, recovery limb contact: RecCon) or grey diamonds (end of acceleration phase: EAP). Contact and liftoff events are characterized as the first time point to cross the 50N threshold (on ascent for touchdown, on descent for liftoff), with the end of acceleration period occurring approximately 300ms following the SlipCon. Time on the x-axis has been adjusted so "0" time is at SlipCon.

1–3, and we assume this was due to lack of familiarity with walking in the laboratory environment during the earliest trials. Therefore, only the third GAIT trial was compared to the PERT trial, with the first two GAIT trials treated as acclimatization trials. Gait velocity at heel contact was compared between the third GAIT and PERT trials using a paired *t*-test to ensure no significant difference in walking speed between conditions. Prior to full statistical analyses, a paired *t*-test was run comparing stability at SlipCon between conditions. We did not expect a between-condition difference in stability at SlipCon, as heel strike triggers platform movement and thus platform movement would not yet influence walking characteristics. As we did not expect any differences between conditions at this time point, we adopted a more liberal alpha of 0.10 for this *t*-test. To control for differences in pre-perturbation stability between conditions, we calculated the differences between stability at SlipCon and RecLift (RecLift-SlipCon), and stability at SlipCon and EAP (EAP-SlipCon). RecLift-SlipCon and EAP-SlipCon were then compared between conditions using paired *t*-tests. We did not explore any sex differences, as previous slip modalities have
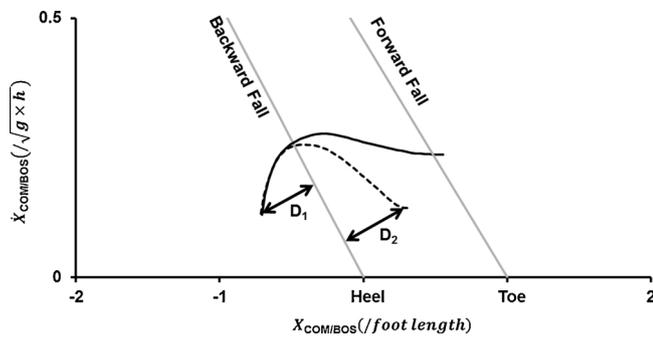
Fig. 2. A representative plot of stability during GAIT and PERT trials. The solid and dashed lines represent GAIT and PERT trials, respectively. Stability is defined as the perpendicular distance to the posterior boundary (backward falls boundary) at a given time point. Both the backward and forward modelled stability boundaries are shown in grey. D1 represents the stability at slip contact time point (SlipCon) in relation to the posterior boundary, wherein no difference was expected. D2 represents the stability at the end of acceleration period time point (EAP) in relation to the posterior boundary, wherein stability was hypothesized to be smaller during the slip trial (as noted by the shorter perpendicular distance to the posterior boundary).

demonstrated no difference between the sexes when studying healthy young adults [8]. Paired t-tests were also used to compare step characteristics (time, distance, velocity) between conditions. Alpha was 0.05 for statistical analyses addressing the study objectives. Group level data are presented as mean ± standard deviation. A post-hoc power analysis was conducted using a previously reported meaningful biological difference of 0.3 for stability at recovery limb liftoff [5]; power was 0.99 for our sample size and measured variability within our sample.

3. Results

3.1. Slip characteristics

Table 1 presents data on the slipping foot characteristics as a result of the motorized platform perturbation. These data are compared alongside slip foot characteristics reported previously for slip modalities of a low friction surface and non-motorized platform [5]. While shear force and coefficient of friction were greater for the motorized platform (depicting a less "slippery" perturbation), slip foot velocity had less variability (standard deviation of 0.01 m/s) compared to previously used methods (standard deviation of 0.43 m/s and 0.49 m/s for low friction surfaces and non-motorized platforms, respectively).

3.2. Stability

Stability at SlipCon was lower in the PERT condition (-0.34 ± 0.08) compared to the GAIT condition (-0.31 ± 0.11) (t (10) = 1.89, p = 0.091). RecLift-SlipCon and EAP-SlipCon stability values are depicted in Fig. 3. Participants exhibited significantly less stability at EAP in the PERT condition compared to the GAIT condition (i.e., statistically significant difference between conditions in EAP-SlipCon; t(10) = -8.29, p < 0.001). During the PERT condition, participants had a stability difference between SlipCon and EAP of
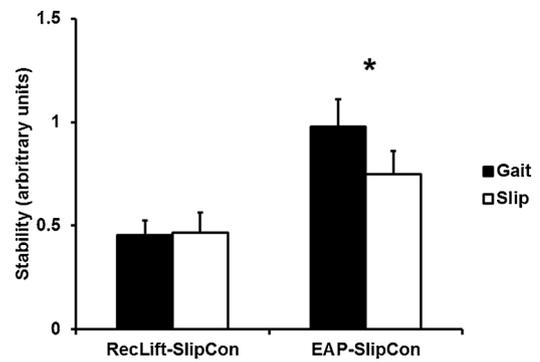

Fig. 3. Mean (SD) stability during both gait (black bar) and slip (white bar) trials. Since stability differences at slip foot contact were p < 0.1, the change in stability between recovery limb liftoff and slip contact (RecLift-SlipCon) and acceleration end phase and slip contact (EAP-SlipCon) was analyzed. Stability difference was only significantly different (*, p < 0.05) between trial conditions at the EAP timepoint. No significant difference was observed in the change in stability between recovery limb liftoff and slip foot contact.

0.75 ± 0.13, compared to a stability difference of 0.97 ± 0.11 during the GAIT condition. This indicates participants' COM did not travel as far forward between SlipCon and EAP during the PERT condition compared to the GAIT condition (Fig. 3). There was no statistically significant difference in the change in stability from SlipCon to RecLift between conditions (p = 0.67).

3.3. Gait characteristics

Gait velocity at heel contact between the third GAIT trial (1.08 ± 0.12 m/s) and PERT trial (1.11 ± 0.17 m/s) was not significantly different (p = 0.22). Step characteristic values are depicted in Fig. 4. Participants had slower steps during the PERT condition (0.76 ± 0.10 m/s) compared to the GAIT condition (1.05 ± 0.14 m/s; t(10) = -7.76, p < 0.001). This was driven by between-condition differences in both step time (t (10) = 3.70, p = 0.0049) and step distance (t (10) = -6.03, p < 0.001). In the PERT condition, participants increased time in single support (step timing of 700 ± 63ms and 601 ± 30ms during PERT and GAIT trials, respectively) while decreasing step distance (step distance of 53.1 ± 7.7cm and 63.0 ± 6.2cm during PERT and GAIT trials, respectively).

4. Discussion

The present study sought to determine the stability and gait characteristics of healthy young adult responses to an unexpected slip-like perturbation during overground walking, delivered by a mechanized platform. We hypothesized that the variability in slipping foot characteristics would be less with the mechanized platform perturbation compared to previously used slip modalities. We also hypothesized that the mechanized slip-like perturbation would induce backwards COM movements in relation to typical overground walking, with values being similar to previous slip modalities. In partial support of the hypothesis, slip foot velocity was found to be extremely consistent (standard deviation of 0.01 m/s) in comparison to previously reported slip foot velocity standard deviation values of 0.43 m/s and 0.49 m/s

Table 1
Slipping characteristics compared between the current study (motorized slip-like perturbation) and previously reported results (low-friction and non-motorized slips; [5]). Peak slip foot velocity (m/s), peak slip foot shear force (N/body weight (bw)), and peak coefficient of friction (CoF) are reported.

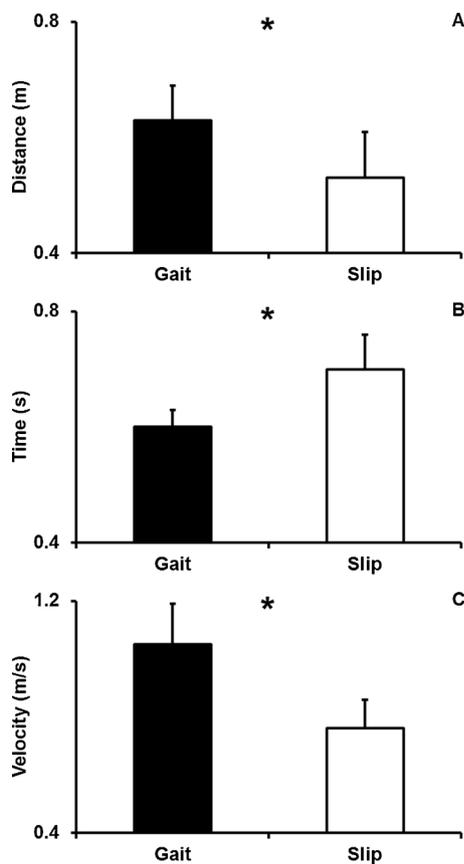|	Motorized Slip-like Perturbation	Low-Friction Slips [5]	Non-Motorized Slips [5]
Peak Slip Velocity (m/s)	0.43 (0.01)	1.38 (0.43)	1.81 (0.49)
Peak Slip Shear Force (N/bw)	−0.14 (0.04)	−0.06 (0.03)	−0.07 (0.02)
Peak CoF	0.16 (0.03)	0.04 (0.01)	0.04 (0.01)

Fig. 4. Mean (SD) stepping characteristics between gait (black bars) and slip (white bars) conditions. Stepping characteristics included **(A)**distance, **(B)** time, and **(C)** velocity. All three stepping characteristics analyzed were significantly different (*, $p < 0.05$) between gait and slip conditions.

for low friction surfaces and non-motorized platforms, respectively. However, our stability analyses revealed non-significant differences in stability between RecLift-SlipCon for PERT and GAIT trials, with only significant differences in stability being observed between EAP-SlipCon (PERT trial demonstrated less stability in comparison to GAIT trial).

Previous slip studies that used low friction surfaces or non-motorized platforms almost always involve a failure to effectively respond to the slip and continue forward gait (e.g., fall backwards into safety harness; [5]). In these studies, stability at recovery limb liftoff is insufficient (negative value in reference to slipping limb posterior boundary), thus the recovery limb usually steps posterior to the slipping limb [5,17]. In our study, participants were young healthy adults; none fell into the safety harness and stability at recovery limb liftoff was positive. As mentioned in the introduction, characteristics of our slip-like perturbation differed from previously established methods of low-friction surface and non-motorized moveable platform perturbations. Firstly, as the entire support surface moved, both lower limbs moved with the platform until the recovery limb liftoff occurred. Thus, there was not an increase in distance between the slipping limb foot and recovery limb foot that often occurs during other slip perturbation modalities. Secondly, the velocity of the slipping limb was not as great as in previous studies (see Table 1). While the overall perturbation magnitude was lower in our study, we believe results still demonstrate that this modality completed its objective of moving stability posteriorly (COM position and velocity in relation to rear base of support) compared to normal overground walking, as demonstrated by smaller stability values at the end of the acceleration phase of the perturbation. This difference demonstrates the perturbation used in our study was still 'slip-like', but was not strong enough to result in a posterior loss of balance or fall.

In addition to changes observed in stability at the end of the acceleration phase of the perturbation, we also found significant changes in stepping characteristics. Young adults decreased their step velocity by increasing step time and decreasing step distance to successfully respond to the slip-like perturbation and avoid a posterior fall. Previous work in slip perturbations have shown similar results, with people of all ages demonstrating shorter step lengths on slippery surfaces to decrease horizontal foot shear forces and reduce the likelihood of slipping [3]. Previous findings have also depicted up to a 10 cm difference in step length between slippery and non-slippery floor surfaces [19]. Furthermore, this is in line with previous work that demonstrates shorter step lengths help reduce the risk of falling when encountering a slip [20]. However, it should also be noted that previous slip paradigms involve negative step distances on the first trial [21], as first trial slips often result in posterior falls into the safety harness. Our study is the first to specifically characterize and compare slipping foot characteristics during motorized platform perturbations to previously established slip modalities. While our paradigm only involved one slip-like perturbation of a lesser magnitude (we propose it represents a milder slip-like occurrence), results are similar to previous studies depicting lower velocities in response to multiple slips (e.g., significantly smaller base of support velocity in response to a retest of a slip [17]).

While our results demonstrate a slip-like perturbation results in significant stability changes (in the posterior direction), a few limitations exist when comparing an entire support surface slip-like perturbation to previously established slip modalities. Firstly, the mechanized perturbation is applied to any limb in contact with the support surface; thus, both lower limbs are perturbed at the onset of the slip-like perturbation until the recovery limb lifts off the ground. Secondly, due to the mechanization of the platform, there is a delay between the software reading the slip foot contact threshold crossing (50 N), and when the platform acceleration exceeds 0.1 m/s^2. This delay was consistently 30–50 ms in duration across all participants. Thirdly, while it does allow for consistent and repeatable perturbation magnitudes (and thus comparison across age groups and clinical populations), outliers in gait velocity (walking extremely fast or slow) may experience a slip-like perturbation that would not be indicative of a slip they would experience in the real world.

In conclusion, our results demonstrate the repeatability and consistency of a motorized support surface for experimental slip-like paradigms. Furthermore, stability and step characteristics confirm the slip-like perturbation resulted in a posterior shift in stability, with appropriate stepping responses being executed by healthy young adult participants to maintain upright balance and overground walking. Future work from our group will examine clinical populations responses to this slip-like perturbation (e.g., individuals with stroke), as it allows us more control and ultimately increases the safety of our clinical population participants.

Conflict of interest

The funding sources did not have any role in the experimental process or in the preparation of the manuscript. There is no conflict of interest for any of the authors.

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