

# Kinematics of the foot during slips

April J. Chambers<sup>a</sup>, Sarah Margerum<sup>a</sup>, Mark S. Redfern<sup>a,b,\*</sup> and Rakié Cham<sup>a</sup>

<sup>a</sup>*Department of Bioengineering, University of Pittsburgh, Pittsburgh, PA, USA*

<sup>b</sup>*Department of Otolaryngology, University of Pittsburgh, Pittsburgh, PA, USA*

**Abstract.** Slip and fall accidents are often listed among the leading generators of injuries. The goals of this study were to (1) describe the foot kinematics during unexpected slips, and (2) to compare the foot kinematics during gait in unexpected slippery environment and when warnings of slippery environments are provided. Five participants walked on dry and glycerol-contaminated floors, while varying the participant's a-priori knowledge of the floor's contaminant condition. Foot kinematics were recorded at 500 Hz from 5 Optotrak LEDs placed on the slipping foot. In unexpected slips, all participants slipped and fell, whereas under the warning conditions, all participants slipped and recovered. Foot kinematics were affected by the warning conditions. More specifically, the heel's vertical velocity just prior to impact and foot-floor angle at heel contact decreased in alert/known slippery environments compared to unexpected slips. Slip distances and velocities were greater in unexpected slips. Finally, the impact of recovery attempts on the heel's kinematics were evident earlier in stance when participants knew or suspected the floor was slippery. Thus, the a-priori perception of slippery surfaces affects the foot kinematics and outcome of slipping.

**Keywords:** Slips, foot, kinematics, falls

## 1. Introduction

Falls precipitated by slipping are a major cause of injury. Lloyd and Stevenson reported that slips and trips cause 67% and 32% of falls sustained by the elderly and young, respectively [14]. Slips and falls were also the leading reason for injury emergency department visits comprising 21% of such visits [17]. Slip, trip and fall related occupational injury ranges from 20 to 40% of disabling occupational injuries in the developed countries [8]. The annual direct cost of fall-related occupational injuries in the USA alone was estimated to be approximately US\$6 billion [8]. Thus, the prevention of such injuries is a high occupational and public health priority.

Slips and falls prevention research has focused on modifying the frictional properties of the shoe-floor interface. The probability of slip depends on the relationship between the friction required during locomotion (required friction) compared with the friction available at the walkway/shoe interface (available friction). Theoretically, as long as the available friction exceeds the required friction, slipping will not occur. However, in order to use this simple relationship to design walkways and prevent slips, an understanding of the frictional requirements is needed, as well as an accurate measure of the available friction. Required friction can be estimated from force plate studies [9,19,23]. These frictional requirements are estimated using the concept of required coefficient of friction (RCOF); defined as the shear forces

\*Corresponding author: Mark S. Redfern, Eye and Ear Institute Building, Room 150, Department of Otolaryngology, University of Pittsburgh, 203 Lothrop Street, Pittsburgh, PA 15261, USA. Tel.: +1 412 647 7923; Fax: +1 412 647 0108; E-mail: redferms@msx.upmc.edu.

divided by the normal forces during a step [19,21]. The peak of this time series (RCOF<sub>peak</sub>) is thought to reflect the value of friction, in terms of coefficient of friction, required to prevent slipping [1,2,15,16,19]. In general, for locomotion of healthy adults, the RCOF<sub>peak</sub> is about 0.18 [16], but will increase for walking on inclined surfaces [22]. Also, the RCOF<sub>peak</sub> will vary for other gait activities such as load carrying or pushing and pulling [19], or for certain populations [2].

Measurement of available friction is another critical part of prevention. Numerous instruments to measure the coefficient of friction of a shoe-floor interface have been developed; however, there is no consensus on the best methods of measurement [6]. Standard models of friction (the Amontons-Coulomb model) that assume friction is solely a material property do not hold. Interface friction of dissimilar complex materials, such as those in shoe soles and floors, coupled with contaminants invalidate Coulomb's law for friction [12]. Rather, shoe-floor interface friction is dependent upon contact area, pressure, temperature, velocity, contact time, and a number of other factors [7]. Thus, the measurement of frictional properties of the environment becomes a complex task.

Recently, a suggested approach to shoe-floor frictional measurement has been to attempt to measure the coefficient of friction (COF) under 'biofidelic' conditions (i.e. conditions that mimic actual gait); in other words, to measure friction using contact areas and motion profiles that reflect actual foot dynamics during gait. At present, there are no devices that measure friction under truly biomechanically relevant conditions; however, there are some devices that have attempted to take this approach [10,11,20,26]. Obviously, understanding the kinematics and kinetics of the shoe during the step cycle, both with and without slipping, is critical if this biofidelic approach is to be realized. Researchers have described key parameters [21]) of the shoe motion during contact [3,13,18,24]. More specifically, variables such as horizontal heel velocity, foot contact angle, and foot angular velocity have been described for walking on dry surfaces. However, there is limited detailed data on the kinematics of the shoe during slips, particularly unexpected slips.

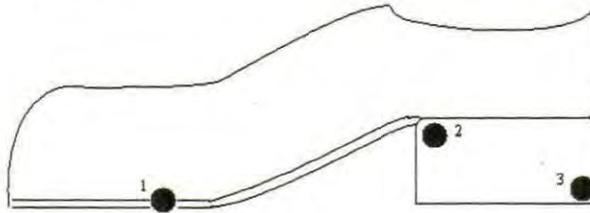
The purpose of this study was to provide detailed kinematics descriptions of the shoe during slipping. The experiment was designed to examine the differences in slipping dynamics when walking onto a glycerol-contaminated floor compared to walking on dry surfaces. In addition, shoe dynamics were recorded during both unexpected slips and slips when the participant knew the surface was contaminated.

## 2. Methods

Five healthy young participants, three females and two males aged 20 to 35 years (mean 23.6 years, standard deviation 2.9 years), participated in this study. Their height and weight ranged from 1.60 to 1.77 m (mean 1.68 m, standard deviation 0.03 m), and from 50.4 to 68.3 kg (mean 62.0 kg, standard deviation 9.2 kg), respectively. Exclusionary criteria included a history of neurological, orthopedic, cardiovascular, or pulmonary disease and any other difficulties that would hinder normal gait.

A vinyl tile walkway was used for the gait experiments. Two Optotrak-3020 motion measurement systems were used to bilaterally record the movements of the left foot during gait on dry and slippery floors. Five Optotrak LEDs were attached to the left shoe of the participant as shown in Fig. 1, and motion data were recorded at 500 Hz. In the slippery conditions, glycerol was applied uniformly onto the floor (0.6 × 0.4 m) in a location such that the left foot came into contact with the slippery area, while the right leg was the trailing limb. All participants wore the same brand/model of polyvinyl chloride (PVC) hard-soled shoes. The static and dynamic COFs of the shoe-floor interface with contaminant were measured using a horizontal pull meter, with values of 0.10 and 0.05 for the static COF and dynamic

Lateral side of the shoe



Medial side of the shoe

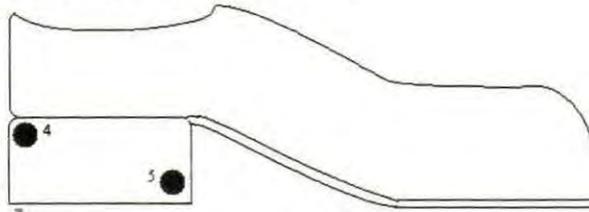


Fig. 1. Placement of Optotrak LEDs on the shoe. Markers 2, 3 and 5 were used to derive the heel's time 3D-space trajectory.

COF, respectively. A harness system with an overhead trolley was used to catch the participant in case of a fall without impeding his or her movements.

All participants were exposed to the same walking protocol. First, written informed consent approved by the Institutional Review Board of the University of Pittsburgh was obtained. Then the participant's left foot was instrumented with the LEDs. The participant was equipped with the safety harness and allowed to practice walking, with the experimenter varying the starting point of the walking trial such that his/her left foot landed onto the flooring area that would be contaminated during the slippery conditions. During this process, the participant was instructed to look straight ahead and walk as naturally as possible at a comfortable pace throughout the experiment. The participant was also instructed (prior to each gait trial included in the experiment) to walk to the start of the gait path, face away from the walkway and listen to loud music for one minute, distracting him/her from the possible application of glycerol onto the floor. At the end of this one-minute waiting period, the participant turned and walked forward while foot motion data was recorded. Finally, the participant was informed that the first few trials would be non-slippery to ensure natural gait.

Two dry trials were conducted ("known dry" conditions). Then, without the participant's knowledge, glycerol was applied onto the floor and another gait trial was conducted ("unexpected slippery" condition). After the unexpected slippery trial, no more information regarding the floor's contaminant condition was revealed for the next six trials, thus the subject did not know what the condition was, but did know that there was a possibility of the contaminant being applied. The first five of the six trials were dry and the sixth was another glycerol condition ("alert slip" condition). A final slippery trial ("known slip" condition) was then run with the participant advised that the floor would be contaminated.

The trajectories of three markers (more specifically marker no. 2, 3, and 5 shown in Fig. 1) were used to derive the time history of the heel's position based on a calibration trial conducted prior to the gait experiments. The position data in the sagittal plane was used to derive instantaneous kinematic variables such as heel position, linear heel velocity, and foot-floor angle. The foot-floor angle was calculated

Table 1  
Impact of environmental condition on selected gait variables

Gait variable	Known dry	Unexpected slip	Alert slip	Known slip
	Mean (standard deviation)			
Foot-floor angle at heel contact (°)	29.0 (3.2)	28.2 (3.0)	21.5 (3.7)	19.7 (5.2)
Maximum rearward sliding velocity (m/s)	-0.24 (0.08)	-0.23 (0.38)	-0.24 (0.14)	-0.35 (0.11)
Maximum forward sliding velocity (m/s)	0.28 (0.02)	1.79 (0.37)	0.80 (0.28)	0.44 (0.29)
Slip distance (mm)	1.8 (1.8)	244.3 (58.7) *	76.9 (30.3)	30.8 (31.9)
Recovery onset identified by decrease in heel velocity (s)	0.023 (0.004)	0.196 (0.038)	0.125 (0.029)	0.144 (0.039)

\* All unexpected slips resulted in falls. The slip distance tabulated here represents the sliding distance from heel contact to the end of the recovery attempt. Participants continued slipping after this point and lost balance.

based on the orientation of the heel-toe vector with respect to the floor in the sagittal plane. A zero-phase least square low pass filter with a cutoff frequency of 50 Hz was applied to the position data prior to deriving heel velocity using a two-time step numerical differentiation routine. The heel contact frame was determined based on the vertical position of LED no. 3 (Fig. 1) compared to the floor.

### 3. Results

The glycerol-contaminated trials resulted in slips under all warning conditions, i.e. the total slip distance was greater than 1 cm (Table 1). A cutoff of 1 cm is often used to categorize the outcome of gait trial as a slip [3,4]. All five participants were unable to regain balance in unexpectedly glycerol-contaminated environments, slipping on average more than 24 cm (Table 1). This is in contrast to the findings recorded under the alert and known slippery conditions: all five participants slipped, recovered and continued walking. The slip distance at the heel, which can be used as a measure of the slip severity, was minimized when participants were certain that the floor was contaminated, i.e. known slippery conditions (Table 1). Similarly, when using the maximum forward sliding velocity (prior to any recovery attempt) as a measure of slip severity, the unexpected slippery conditions generated the most severe slips, followed by the alert and known slippery conditions, respectively (Table 1).

The overall shape of the heel's trajectory and its sliding patterns observed at and shortly after heel contact were similar in glycerol-contaminated and dry environments. The forward-rearward-forward sliding pattern of the heel reported in [3] was also observed here in dry and slippery environments under all warning conditions (Figs 2 and 3). At heel contact, the heel was, in general, moving in the forward direction as it was brought down onto the floor (positive horizontal heel velocity shown in Fig. 4). In dry no-slip conditions, the heel came to a stop, on average, 25 to 35 ms after heel contact.

Under the alert and known slip conditions, participants were able to recover from mean peak forward sliding heel velocities of 0.8 and 0.4 m/s, respectively (Table 1). On average, this peak velocity occurred approximately 135 ms into stance. Glycerol-contaminated conditions produced slip distances ranging from 5.0 to 11.2 cm in alert slip conditions, and from -0.3 (rearward slip) to 7.1 cm when participants were certain that the floor was slippery. Typical heel position and velocity profiles of slip-recovery events under alert and known slip conditions indicated recovery by about 190 to 250 ms after heel contact (Fig. 2, Fig. 3).

In slips resulting in falls, i.e. unexpected slippery conditions, participants also attempted to regain balance. This recovery attempt was evident as the participant was able to slow down the heel's slipping motion, achieving a local minimum heel velocity recorded between 240 to 300 ms after heel contact, at which time the foot accelerated again in the forward direction, eventually leading to a fall (Fig. 2 and

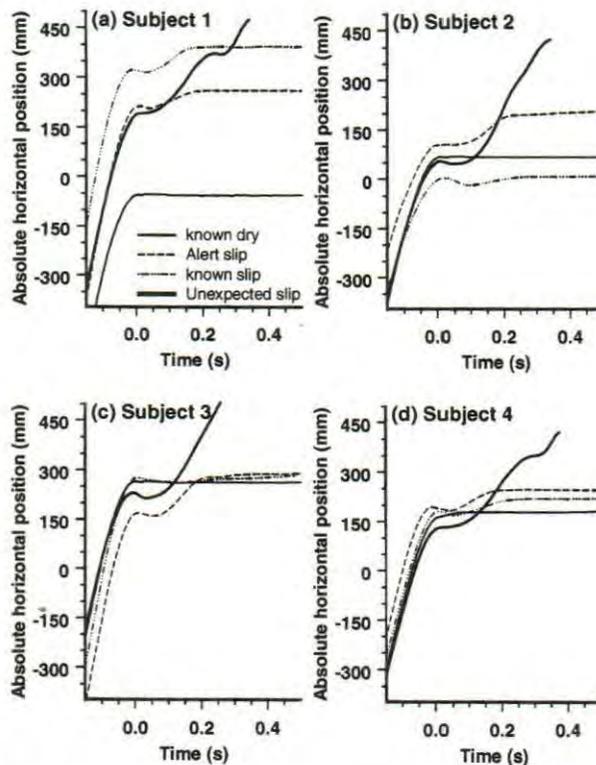


Fig. 2. Typical profiles of the heel trajectory in the horizontal direction. (Time “0 s” represents heel contact of the leading foot onto the floor). Participants slipped across greater distances when walking onto unexpectedly slippery floors (slip-fall outcomes) compared to gait onto suspected (“alert”) or known slippery environments (slip-recovery outcomes). Note that recovery in each trace can be identified as the time when the horizontal position is constant

Fig. 3). Prior to this failed recovery attempt within the first 200 ms, mean peak forward sliding velocities ranged from 1.5 to 2.3 m/s, and slip distances exceeded 18–32 cm (averages shown in Table 1).

Warning conditions appear to impact several aspects of the foot kinematics during slips. At heel contact, the vertical velocity of the heel decreased in alert/known slip conditions compared to gait on unexpectedly slippery floors. More specifically, vertical heel velocity decreased on average from 0.3 m/s to 0.07 m/s from unexpected to alert/known slippery floors (Fig. 4).

Foot-floor angle at heel contact is another variable that was affected by the perceived danger of slipping. The foot contacted the floor at a mean angle of about  $29^\circ$  during known dry conditions (Table 1, Fig. 5), then continued to rotate to foot-flat. The participant’s foot impacted the floor at a foot-floor angle of  $23^\circ$  and  $19^\circ$  in alert and known slippery environments, respectively (Table 1). As depicted in the examples of Fig. 5, participants were able to rotate their foot flat onto the floor within 150 ms into stance in the majority of the trials (dry and slippery conditions). However, it is interesting to note that in slip-fall events during gait on unexpectedly slippery conditions, this phase was delayed for all participants (Fig. 5). For example, participant 3 was not able to reach foot flat position until 400 ms into stance (Fig. 5c). Other less extreme examples are shown in Fig. 5.

The onset of the corrective responses generated in an attempt to control the sliding motion of the foot and to prevent falling was also affected by the warning conditions. Those corrective responses were generated earlier in stance when the participant suspected or knew the floor was slippery compared to gait

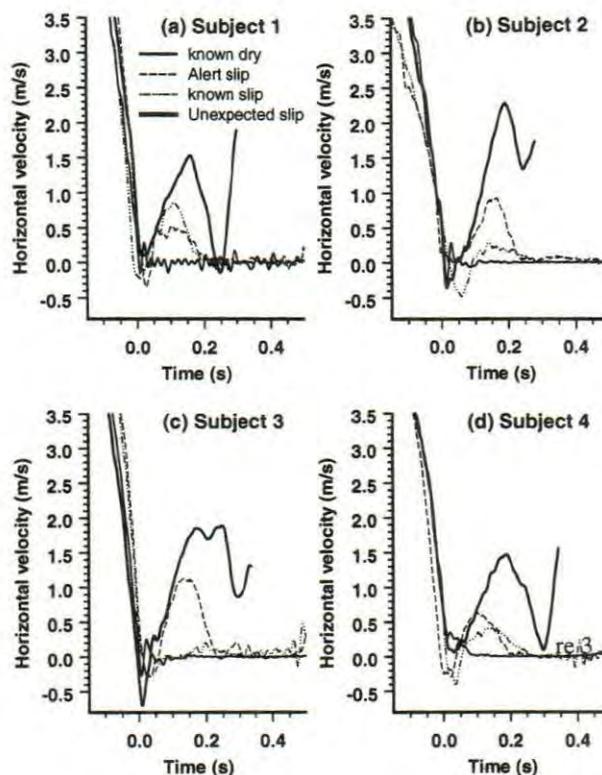


Fig. 3. Typical profiles of the heel velocity in the horizontal direction. (Time “0 s” represents heel contact of the leading foot onto the floor). Under the alert and known slip conditions, participants were able to recover within 200 to 250 ms after heel contact. In slips resulting in falls, i.e. unexpected slippery conditions, the participant attempted to recover, achieving a local minimum heel velocity between 240 and 300 ms after heel contact, at which time the foot accelerated again, eventually leading to a fall. The greatest sliding velocities were recorded under the unexpected slippery conditions.

without a-priori knowledge of the floor’s contaminant condition. For example, the onset of the recovery attempt can be depicted by the time at which the heel’s velocity started decreasing after reaching peak values (Table 1, Fig. 3). This onset occurred nearly 200 ms after heel contact in unexpected conditions, i.e. on average 50 to 70 ms later than responses generated during alert/known slippery conditions (Table 1).

#### 4. Discussion

This study described the kinematics of the foot during slipping. Furthermore, this study investigated the impact of a-priori knowledge of the floor’s slipperiness condition on the kinematics of the foot slipping during gait on glycerol-contaminated floors. Kinematic gait variables of interest included heel position, velocity and foot orientation. Slip distances and velocities were greater in unexpectedly slippery environments compared to known-slippery conditions. In addition, participants had more difficulty rotating the foot flat onto the floor during unexpected slips.

The protocol used in this study proved the feasibility of reproducing unexpected slips in laboratory environments, as the heel dynamics just prior to and at heel contact were similar during gait onto known dry floors and in unexpectedly slippery environments. The perception of the danger of slipping affected the foot kinematics significantly. More specifically, the severity of the slip, quantified by the slip distance

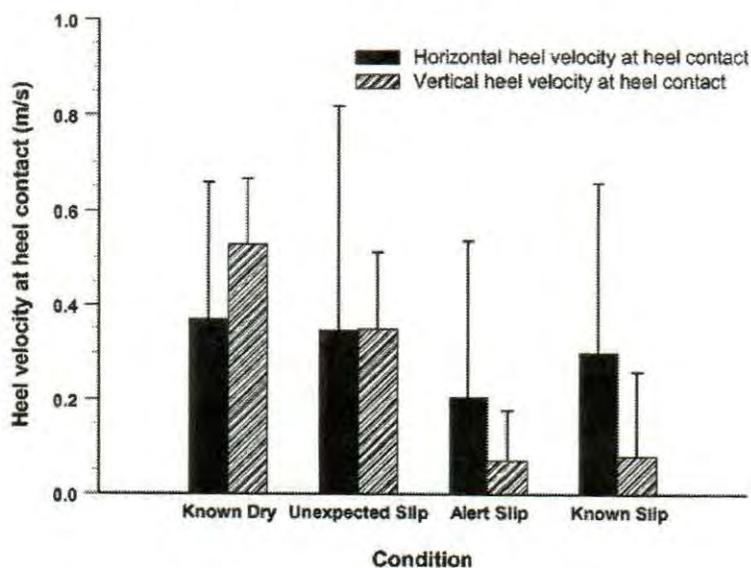


Fig. 4. Average heel velocity and standard deviation derived at heel contact. At heel contact, the vertical velocity of the heel decreased in alert/known slip conditions compared to gait onto unexpected slippery floors.

and peak forward sliding velocity, decreased when participants were aware of or suspected slippery surfaces. Thus, all unexpected slips resulted in falls, whereas alert/known slippery conditions generated slip-with-recovery events. Feedforward control was also probably engaged, where participants adapted his/her gait, walking "more cautiously" when they suspected or knew the floor was slippery, increasing their recovery chances when the slip occurred. Proactive gait adaptations adopted in environments perceived to be slippery included reduced vertical heel velocity and foot-floor angle at heel impact. In addition, feedback control factors are believed to contribute toward difference in sliding velocities and slip distance. These responses probably involve attentional factors in the sensorimotor process of recovery. The biomechanical responses, i.e. body kinematics and movement patterns, can be thought of as motor programs that are initiated in response to some sensory cue of the perturbation. The responses are engaged more efficiently if one anticipates the slip and has the appropriate response prepared to be engaged. This is confirmed by the shorter recovery onset times during the alert condition; recovery reactions were generated about 50 to 70 ms earlier in stance compared to responses in unexpectedly slippery environments. Interestingly, the impact of the corrective reactions on heel velocity was not evident within the first 100 to 150 ms into stance even when anticipating slippery surfaces. In fact, the heel's sliding patterns (e.g., biphasic shape of the heel's velocity profile) were similar under all warning conditions early in the stance period, suggesting the subjects' inability to counteract the slipping perturbation just after heel contact.

The kinematic profiles and parametric values presented in this paper can be used to develop slip resistance testing devices that are more biofidelic. Improvements in slip testing will need a better understanding of actual foot dynamics if the measures are to be able to predict actual slips [7]. Slip resistance testers that currently try to measure slip resistance under biomechanically relevant conditions do not meet the kinematics described in this paper [9,18,20]. However, with this additional information new testing can be developed.

In general, the results reported here are supported by previously published findings. Slip distance and peak sliding velocity thresholds are often used to characterize perturbations beyond which balance is

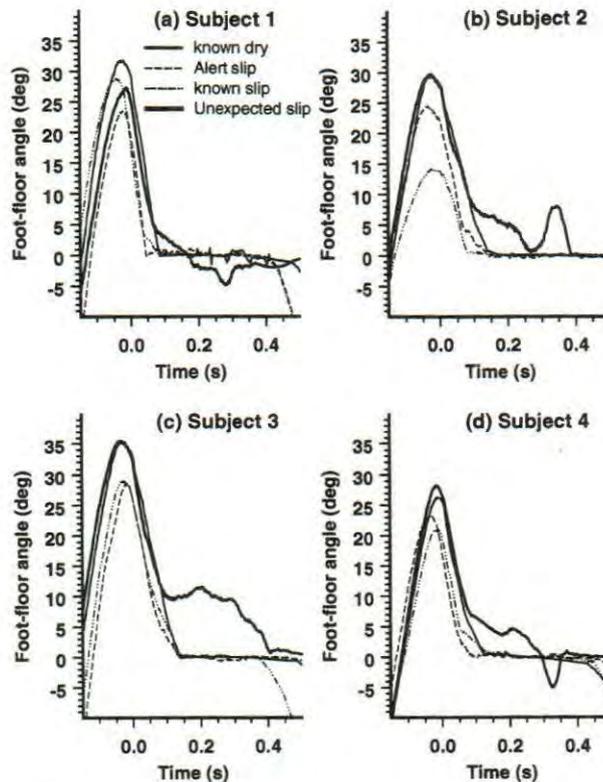


Fig. 5. Typical profiles of the foot-floor angle. (Time "0 s" represents heel contact of the leading foot onto the floor). In alert and known slippery environments, the foot impacted the floor at a reduced foot-floor angle. In slip-fall events during gait on unexpectedly slippery conditions, the foot reached a flat position onto the floor later in stance compared to gait in dry and alert/known slippery environments.

irrecoverable. For example, slipping across a distance greater than 10 to 15 cm in Perkins' experiments resulted in falls [18]. Similarly, Strandberg and Lanshammar [25] suggested that a slip is likely to result in a fall if the slip distance exceeds 10 cm or the peak heel sliding velocity is greater than 0.5 m/s [25]. More recently, Cham and Redfern [3] reported that 90% of all of their slip-with-recovery trials (level and inclined oily surfaces) were associated with a slip distance less than or equal to 9.4 cm [3]. Moreover, in that same investigation, any attempted recovery from slip distances beyond 14 cm and peak forward sliding velocities greater than 0.7–0.8 m/s was unsuccessful. In this study, all fall trials were characterized by slip distances greater than 18 cm and peak sliding velocities ranging from 1.5 to 2.3 m/s, which is consistent with previously published findings. Furthermore, only one (out of 10) slip-with-recovery trial was characterized by a slip distance beyond 10 cm (11 cm). It is interesting to note however that, in 50% of the slip-with-recovery events, sliding velocities greater than 0.5 m/s were recorded, two trials with peak velocities exceeding 0.8 m/s, the maximum being 1.1 m/s. This is believed to be the result of anticipation: participants reacted faster when they suspected or knew the floor was contaminated, and were thus able to recover from perturbations of significant magnitude.

Another variable that has been subject of previous considerations is the foot orientation with respect to the floor. Leamon and Son [13] reported a foot-floor angle of approximately  $30^\circ$  at heel contact, which is in agreement with the findings reported here ( $28\text{--}29^\circ$ ) during gait onto known dry floors and in unexpectedly slippery environments [13]. However, those values are greater than previously published

results [3,25]. Anticipation effects may be at the source of this apparent disagreement among studies, as foot-floor angle at heel contact was shown (here and in [5]) to decrease when participants anticipate slippery surfaces. Interestingly, Cham and Redfern [3] reported that all participants were able to rotate their foot flat onto the floor even in the trials that resulted in falls. Perkins [18] on the other hand, discussed occasional fall trials (associated with large impact foot-floor angles) during which the foot never reached foot flat position [18]. In this study, foot-flat position was reached in fall outcomes (i.e. unexpected slips), however at a significant later time in stance compared to normal gait in both dry no-slip conditions and in slip-with-recovery events (alert/known slippery conditions). This may be due to the greater foot-floor angle recorded at heel contact during unexpected slippery conditions. Another explanation may be stiffer ankle/knee joints during the alert/known slips. Theoretically, stiffer joints would be associated with decreased slipping, better control of the ankle joint and increased ability to generate the ankle momentum needed to rotate the foot flat onto the floor.

## 5. Conclusions

In conclusion, this study described heel contact dynamics during gait in unexpected, suspected and known slippery environments. Specifically, the study showed: 1) slip characteristics of the foot are altered by a priori knowledge of conditions, resulting in falls for unexpected conditions and recoveries in alert conditions, 2) slip distances were less in known conditions compared to alert conditions, 3) foot kinematics at impact are modified during alert and known slippery conditions, including heel contact velocities and rotation angles, and 4) active recovery attempts are engaged earlier in the slip when the conditions are alert or known compared to the unknown condition. This information is valuable for the development of slip resistance testers that are designed to reproduce the dynamics of the human foot during slipping in an attempt to generate biomechanically-relevant measures of friction. Further, the study suggests that the perception of the environment has an impact on recovery outcome through both preparatory adjustments in gait and the efficiency of recovery responses once a slip is initiated.

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### CONTENTS

Guest Editorial	i
<i>R. Grönqvist, S. Matz and M. Hirvonen</i> Assessment of shoe-floor slipperiness with respect to contact-time-related variation in friction during heel strike	197
<i>S.S. Chiou, A. Bhattacharya, C.-F. Lai and P.A. Succop</i> Effects of environmental and job-task factors on workers' gait characteristics on slippery surfaces	209
<i>A.J. Chambers, S. Margerum, M.S. Redfern and R. Cham</i> Kinematics of the foot during slips	225
<i>C.S. Pan, S. Chiou and S. Hendricks</i> The effect of drywall lifting method on workers' balance in a laboratory-based simulation	235
<i>L. Kincl, A. Bhattacharya, P. Succop and A. Bagchee</i> The effect of workload, work experience and inclined standing surface on visual spatial perception: Fall potential/prevention implications	251
Author Index Volume 3	261

