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ORIGINAL RESEARCH

Three-Dimensional Shoe Kinematics During Unexpected Slips: Implications for Shoe–Floor Friction Testing

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OCCUPATIONAL APPLICATIONS This study described the three-dimensional kinematics of the shoe during slipping and compared them to shoe kinematics specified by standard methods for coefficient of friction testing. At the time of slip initiation, substantially higher sagittal-plane shoe–floor angles and more medial shoe velocity occur than what have previously been reported. These results suggest that standard slip-testing methods should be reexamined so they better align with the state of the shoe when it begins to slip. The incongruence between actual slips and testing methods could lead to shoe designs that perform well during friction testing but are sub-optimal during an actual slip.

TECHNICAL ABSTRACT ***Background***: Shoe design is an important component of slip and fall prevention efforts. Evaluating the slip resistance of shoes in a way that is relevant to slipping accidents requires a comprehensive understanding of the shoe biomechanics during slipping. Limitations in previous studies on this topic include omission of kinematics outside the sagittal plane, which may impact coefficient of friction measurements, and the use of multiple slip perturbations, which can lead to kinematic changes due to anticipation and adaptation. ***Purpose***: The purpose of this study was to describe the three-dimensional kinematics of the shoe during unexpected slips to better inform shoe–floor coefficient of friction testing. ***Methods***: Thirteen subjects were exposed to a low friction fluid contaminant while wearing shoes without tread. The sliding speed, direction of sliding, sagittal-plane shoe–floor angle, and frontal plane shoe–floor angle were described at the moment of slip initiation, peak slipping speed (PSS), and 50% of the peak slipping speed (½ PSS). Statistical comparisons assessed whether the kinematics obtained from standard shoe coefficient of friction methods fell within the 95% confidence interval of the measured shoe kinematics at each time point. ***Results***: At least one of the kinematic variables used during standard friction testing methods deviated from the observed kinematics at each time point. Specifically, the central tendency of the observed slips was characterized with a higher sagittal plane shoe angle at slip initiation, a more medial sliding

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direction at slip initiation, and a higher sliding speed at ½ PSS and PSS than those used during standard shoe friction testing methods. ***Conclusions***: Shoe kinematics in friction testing standards exhibit differences with shoe kinematics during actual slips. Thus, a need exists for revisiting the kinematic conditions used in slip testing based on rigorous biomechanical studies of slipping.

KEYWORDS Slips and falls, shoe kinematics, shoe friction testing

INTRODUCTION

Slips are a leading contributor to falls (Courtney, Sorock, et al., 2001) and resulting injuries—especially in the work place. According to recent Bureau of Labor Statistics reports, slips, trips, and falls are the leading cause of fractures (U.S. Department of Labor, Bureau of Labor Statistics, 2015b). Same-level falls have an incidence rate of 29.3 per 10,000 full-time employees each year (U.S. Department of Labor, Bureau of Labor Statistics, 2015a), and slips are estimated to be a contributing factor in 40% to 50% of same-level falls (Courtney, Sorock, et al., 2001). Furthermore, workers' compensation costs for same-level falls were estimated to be $10.2 billion in 2015 (Liberty Mutual Research Institute for Safety, 2016), and total lifetime costs of falls occurring in the United States during 2013 were estimated at $180 billion (Florence, Haegerich, et al., 2015; Florence, Simon, et al., 2015). Producers of footwear and flooring materials have responded to this problem by producing and labeling products as "slip-resistant." While shoe testing standards have been developed to quantify the effectiveness of these products (American Society for Testing and Materials [ASTM], 2011; International Standards Organization, 2012), ensuring these test methods mimic actual slips is critical in mediating the problem.

The contributing factors to slipping can be broadly categorized to those influencing gait and slipping biomechanics and those influencing the tribology of the shoe–floor interface. The occurrence of a slip can be predicted by comparison of the required coefficient of friction (RCOF), which is a net measure of the ground reaction forces caused by a gait pattern, to the available coefficient of friction (ACOF), a measure of the coefficient of friction (COF) at the shoe–floor interface (Hanson et al., 1999; Burnfield & Powers, 2006; Tsai & Powers, 2008). Gait parameters such as walking speed, cadence (Moyer et al., 2006; Holbein-Jenny et al., 2007), step length (Andres et al., 1992; Llewellyn & Nevola, 1992; Brady et al., 2000; Lockhart et al., 2003; Moyer et al., 2006), shoe–floor angle (in the sagittal plane) at heel strike (Strandberg, 1983; Manning et al., 1988; Redfern & Rhoades, 1996; Cham & Redfern, 2002a; Chambers et al., 2003; Marigold et al., 2003; McGorry et al., 2008; McGorry et al., 2010) and its derivative (McGorry et al., 2010), heel velocity at heel strike (Cham et al., 2000; Cham & Redfern, 2002b; McGorry et al., 2008; McGorry et al., 2010), heel acceleration at heel strike (Redfern & Rhoades, 1996; Beschorner & Cham, 2008), the relationship between a person's center of mass and the center of pressure or heel contact point (Grönqvist, Abeysekera, et al., 2001; Grönqvist, Chang, et al., 2001), and gait adaptations related to the awareness of slip-potential (Cham & Redfern, 2002a; Chambers et al., 2014) have been demonstrated to influence a person's RCOF and/or the severity of slips. The tribology of the shoe–floor interface is known to be affected by a wide range of biomechanical and environmental factors as well as a person's footwear. Specifically, biomechanical variables affecting ACOF include sliding speed (Redfern & Bidanda, 1994; Beschorner et al., 2007; Beschorner et al., 2009; Moore et al., 2012; Blanchette & Powers, 2015b), shoe–floor angle in the sagittal plane (Redfern & Bidanda, 1994; Beschorner et al., 2007; Blanchette & Powers, 2015b), vertical force (Redfern & Bidanda, 1994; Beschorner et al., 2007; Blanchette & Powers, 2015b), and the contact time between shoe and floor (Grönqvist et al., 2003). Environmental factors that influence ACOF include flooring material (Li et al., 2004; Li et al., 2007), floor roughness (Chang, Kim, et al., 2001; Cowap et al., 2015; Moghaddam et al., 2015), and fluid present (Hanson et al., 1999; Chang, Grönqvist, Leclercq, Myung, et al., 2001; Beschorner et al., 2007; Cowap et al., 2015) on the floor. Footwear parameters that influence the available friction include the presence of tread (Grönqvist, 1995; Beschorner & Singh, 2012), tread design (Li & Chen, 2005; Li et al., 2006; Beschorner & Singh, 2012; Blanchette & Powers, 2015a), and material hardness (Tsai & Powers, 2008; Moghaddam et al., 2015).

The methodology used to quantify ACOF has a substantial impact on the measured values and their relevance to actual slips. Previous research has demonstrated substantial variation across tribometers in their ability to rank the slipperiness of floor surfaces consistent with results of human slipping studies (Powers et al., 2007; Powers et al., 2010). Because of the dependence of the COF on the kinematics between the shoe and floor, approximating these conditions has been suggested as necessary to arrive at relevant measures of ACOF (Strandberg & Lanshammar, 1981; Strandberg, 1983; Grönqvist et al., 1989; Chang, Grönqvist, Leclercq, Brungraber, et al., 2001; Courtney, Chang, et al., 2001; Beschorner et al., 2007). Developing methods that approximate the conditions of a slip require detailed knowledge of slipping kinematics.

Sagittal-plane shoe kinematics during human slipping events have been previously reported and have been used to guide slip-testing methods. The shoe kinematic variables that have previously been reported are vertical velocity of the heel (Cham & Redfern, 2002b; Chambers et al., 2003), sliding velocity of the heel in the walking direction (Strandberg & Lanshammar, 1981; Cham & Redfern, 2002b; Chambers et al., 2003; McGorry et al., 2008; McGorry et al., 2010), and the shoe–floor angle in the sagittal plane (Strandberg & Lanshammar, 1981; Cham & Redfern, 2002b; Chambers et al., 2003; McGorry et al., 2008; McGorry et al., 2010). These kinematic variables have been reported at the time of heel strike (Strandberg & Lanshammar, 1981; Cham & Redfern, 2002b; Chambers et al., 2003; McGorry et al., 2008; McGorry et al., 2010), minimum anterior velocity (Strandberg & Lanshammar, 1981), maximum anterior velocity (Strandberg & Lanshammar, 1981; Cham & Redfern, 2002b), and the transition between posterior and anterior velocity (Cham & Redfern, 2002b). The time of slip initiation, which has been reported as either the minimum anterior velocity (Strandberg & Lanshammar, 1981) or the transition between posterior and anterior velocity (Cham & Redfern, 2002b), is thought to be the critical time period relevant to slipping, since this represents the time when the friction available between the shoe and floor is unable to decelerate the shoe and prevent a slip from propagating (Grönqvist et al., 1989; Wilson, 1996). Based on previous human slipping research, Grönqvist and colleagues (1989) selected a slipping speed of 0.4 m/s and shoe–floor angle of 5°, and current whole-shoe testing standards typically use a sliding speed of 0.3 m/s with a shoe–floor angle of 7° (ASTM, 2011; International Standards Organization, 2012).

Existing reports of shoe kinematics during slipping have largely ignored motions outside the sagittal plane despite the fact that these kinematic variables could impact ACOF. Existing research hints that kinematics outside the sagittal plane during slipping could be substantial and could have an impact on slip-testing results. For example, Troy and Grabiner (2006) reported that the mean peak medial–lateral sliding speeds were 0.56 m/s, which was about a third of the average peak anterior–posterior sliding speeds (1.58 m/s). Substantial leg internal–external rotation angles were also reported (14.7°), which suggests that shoe rotations may also be occurring in the horizontal (transverse) plane (Troy & Grabiner, 2006). Medial–lateral sliding speeds, frontal plane kinematics, and transverse plane kinematics have not been previously reported at the critical moment of slip initiation, which limits their utility to guide slip-testing. Previous research has demonstrated that friction is dependent on the tread orientation (Blanchette & Powers, 2015a), which suggests that sliding direction would influence measurements. However, the benefits of such a shoe orientation may not be realized during an actual slip if the shoe velocity also includes a medial–lateral velocity since this would change the angle between the shoe tread and the direction of motion. Frontal plane shoe angles are also relevant since these angles would affect the contact region between the shoe and the floor. Shoe tilt in the frontal plane in the inversion direction would alter the contact region, which is known to influence ACOF (Strandberg, 1983; Grönqvist, 1995; Grönqvist & Hirvonen, 1995; Blanchette & Powers, 2015a). Therefore, understanding these kinematics is important for developing slip-testing methods that better mimic slips and guide shoe outsole designs that increase ACOF.

This study aims to report three-dimensional kinematics of slipping including the sliding speed of the heel, direction of heel velocity relative to the shoe orientation, sagittal plane shoe angles, and frontal plane shoe angles. Particular emphasis is on reporting these kinematic variables at the time of slip initiation in order to better inform shoe friction testing methods on the state of the shoe at this critical moment. We also assessed the consistency between shoe kinematics in current standards for whole shoe COF testing versus observed human slips.

METHODS

Out of 18 recruited subjects, data from 13 subjects were analyzed (7 female, mean ± standard deviation: age 23.2 ± 4.1 years, height 1.72 ± 0.07 m, mass 70.3 ± 11.1 kg). Recruited subjects were without any neurologic, cardiovascular, pulmonary, or vestibular problems to ensure both normal walking and the safety of the subjects. Potential subjects were also excluded if they had osteoporosis or orthopedic problems that prevented normal walking. Data from five subjects were excluded based on the following criteria: (1) their left heel did not land within the fluid-contaminated region; or (2) the non-treaded shoes were worn during the second exposure to the contaminant and they experienced a slip (as defined later in the methods) during the first exposure. The rationale for this second criterion was that subjects who experience a slip may be less likely to return to their baseline gait than subjects who did not experience a slip. Informed consent was obtained from the subjects prior to testing. The study was approved by the University of Pittsburgh Institutional Review Board.

Subjects walked across an 8-meter-long vinyl walkway at a self-selected speed while wearing a safety harness. Subjects were exposed to a fluid surface contaminant once while wearing a standard pair of shoes (Fig. 1) with tread and once while wearing the same shoe type with the tread removed ("non-treaded"). The shoes were advertised as slip-resistant, and the soles of the shoes were made of a rubber compound with a Shore A hardness of 58. The tread was completely removed from the non-treaded shoes via an abrasion process using an abrasive moving belt. The wear process was paused frequently to minimize heat buildup in order to avoid altering the material properties of the shoe material. The shoes and the tread removal procedure are further described in a previous publication (Beschorner et al., 2014). Five dry trials preceded the first exposure to a fluid contaminant.

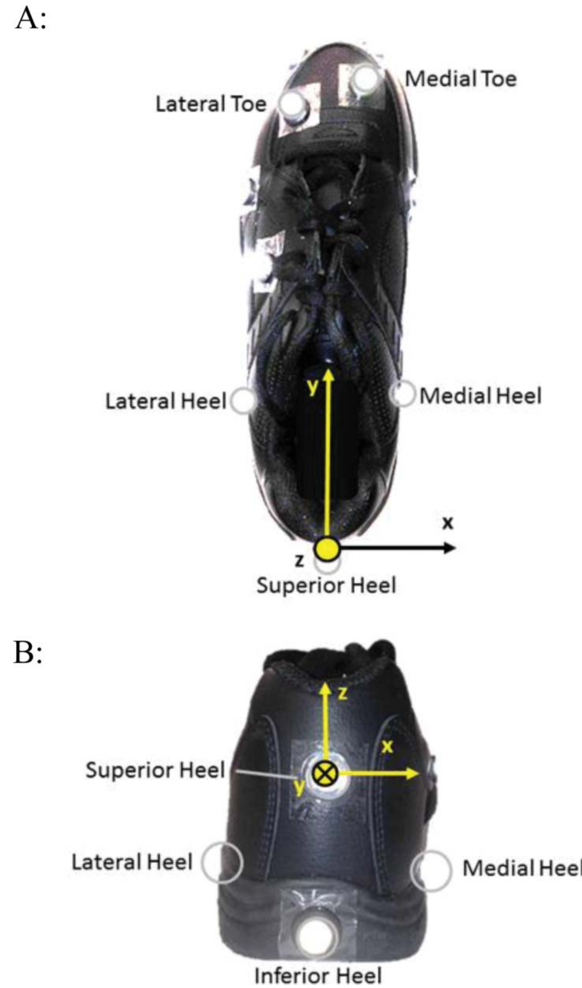

FIGURE 1 **Reflective marker locations placed on the shoe from (A) top view and (B) posterior view.**

Prior to these trials, subjects were informed that the first several trials would be dry and were not given any subsequent instruction. At least ten recovery dry trials were completed after the first exposure, which were followed by a second exposure. Subjects were told after the first fluid contaminated trial that this next set of trials would be dry. The number of dry trials after the first exposure was chosen based on previous research indicating that young adults return to their baseline RCOF eight dry trials after being exposed to a contaminant (Chambers et al., 2014). The order in which subjects wore the treaded and non-treaded shoes was randomized. Only trials from the non-treaded shoes were considered in the present analysis since few subjects experienced a slip with the treaded shoes (Beschorner et al., 2014). The slippery condition was created using 85 ml 90%:10% glycerol:water solution spread across a 610 × 610 mm vinyl floor section. The subjects' starting position was adjusted during the dry trials so the left shoe would hit within the region where the contaminant was applied. The lights were dimmed during all trials to decrease the likelihood of the subjects noticing the contaminant. Subjects faced the wall and listened to music between each trial to prevent visual or audible cues regarding the application of the contaminant.

Kinematic data for six shoe-mounted markers (Fig. 1) were tracked with a 14-camera motion capture system (Vicon MX; Vicon Industries, Inc., Hauppauge, NY, USA) at 120 Hz. The locations of these markers included the posterior portion of the calcaneous (superior heel), a point directly inferior from the heel marker just above the ground (inferior heel), on the medial and lateral side of the heel of the shoe about one third of the shoe length anterior from the heel (medial heel and lateral heel), and two locations on the forefoot (point of shoe immediately superior to the first distal phalanx, medial toe, and point of shoe immediately superior to third distal phalanx, lateral toe). Two other markers were placed on the lateral portion of the forefoot (Fig. 1) for redundancy. All data were filtered using a zero-phase shift 4th order low-pass Butterworth filter with a cutoff frequency of 6 Hz.

Three time points were used for parameterizing the kinematic analyses: (1) slip initiation; (2) the time of peak resultant slip speed (PSS); and (3) the first time the resultant heel speed reached half of PSS (½ PSS). Slip initiation was defined as the time when the resultant slip speed reached its first local minimum after heel strike. The time of the PSS was defined as the moment when the heel reached its peak speed over the slip duration. Slip initiation and PSS were chosen as measures of interest because slip initiation is the moment when the ACOF is insufficient to decelerate the shoe, and PSS is a measure of slip severity (Strandberg & Lanshammar, 1981; Lockhart et al., 2003; Moyer et al., 2006). In order to get an intermediate time point, the time where the slipping velocity first reached ½ PSS was also used to parameterize the time-series kinematics.

The kinematic variables that were analyzed included sliding speed, shoe angles, and the velocity direction relative to shoe orientation. The sliding speed (magnitude of sliding velocity) was calculated based on the inferior heel marker. The angle between the shoe and the floor in the sagittal plane (sagittal angle), the shoe rotation angle in the frontal plane (inversion/eversion angle), and the angle between the longitudinal (y-axis)

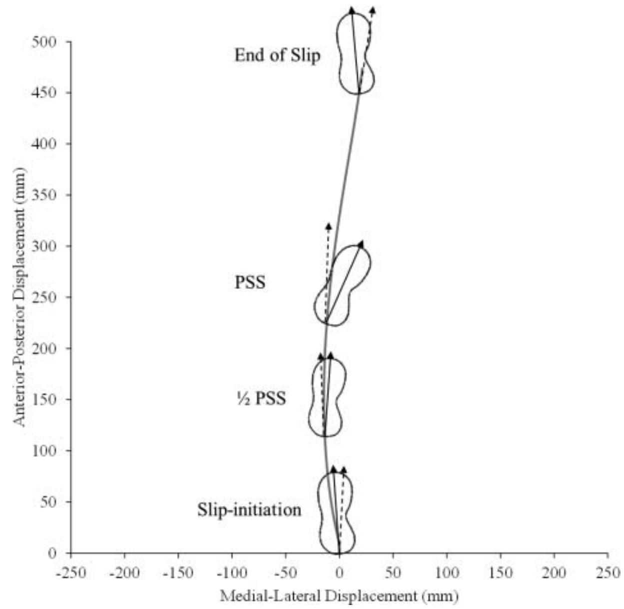

FIGURE 2 **A plot of representative left shoe kinematics during a slip including the trajectory of the heel marker (solid line), the orientation of the shoe (solid arrow), and the instantaneous velocity vector (dashed line arrow). The angle between these two vectors is the lateral velocity angle. In this figure, a lateral angle occurred at ½ PSS and PSS, whereas a medial velocity angle occurs at slip initiation and end of slip.**

of the shoe and the instantaneous velocity vector (lateral velocity angle; Fig. 2) were also determined. Sagittal angles and inversion/eversion angles were calculated using the Euler angle method (Pio, 1966). The global coordinate system consisted of the gait progression direction (Y); the upward vertical direction (Z); and a vector to the right of forward progression (X). The local coordinate system consisted of the longitudinal axis of the shoe (y), which was defined as the line from the superior heel marker to the midpoint between the lateral and medial toe markers (Fig. 1); an axis perpendicular to both the y-axis and the vector connecting the superior heel marker to the lateral heel marker (pointing up, z-axis); and a third mutually-perpendicular vector pointing to the right (x). Angles from the static trial, during which the subject's feet were approximately aligned with the global coordinate system, were subtracted from the dynamic angles to eliminate effects due to subtle differences in marker placement across subjects. The transverse angle of the shoe relative to the global reference frame and the vertical displacement/velocity were not reported since these variables are not particularly relevant to shoe–floor friction testing. The transverse angle of the shoe orientation relative to the global reference frame is less important than the sliding direction relative to shoe orientation (i.e., lateral velocity angle) since most flooring used in friction testing lacks surface features with a particular directionality (ASTM, 2012), whereas tread often does exhibit directionality (Li & Chen, 2005; Blanchette & Powers, 2015a). Furthermore, vertical displacement/velocity of the shoe influences the vertical force applied to the shoe, which is typically separately controlled in slip-testing (Beschorner et al., 2007). All kinematic parameters were calculated at slip-initiation, ½ PSS, and PSS.

Slip distance, step length, and shoe angle were quantified to confirm that a slip occurred in each trial and assess potential anticipation of a slip. A slip was defined as having a resultant sliding distance of at least 3 cm over its duration (Leamon & Li, 1990; Beschorner et al., 2016). The slip duration was considered to be from slip initiation to the end time, defined to either be the second local minimum in resultant heel sliding speed after heel strike or the time when the slipping shoe slid off the contaminated tile (Moyer et al., 2006; Beschorner et al., 2016). In order to quantify whether subjects changed their gait kinematics in anticipation of a slip, step length—defined as the anterior/posterior distance between the right and left heels—and the shoe–floor angle of the left (slipping-side) foot in the sagittal plane were calculated at heel strike with the contaminated tile for both the slippery trial and the last dry trial before the slippery trial.

Statistical analyses were used to assess the distribution of data, whether standard testing conditions were within the confidence intervals observed during slipping, and whether anticipation effects were observed. A Shapiro-Wilk test was used to assess normality of each kinematic variable at each time point. A single sample *t*-test was used to determine if kinematics used in standard shoe COF testing (sagittal angle = 7°, inversion/eversion angle = 0°, lateral velocity angle = 0°, sliding speed = 0.3 m/s; ASTM, 2011; International Standards Organization, 2012) were within the 95% confidence interval of the slipping kinematics at each time point of interest. For variables that were not normally distributed (i.e., Shapiro-Wilk test had a $p < 0.05$), non-parametric analyses (Wilcoxon Signed Rank median test) were performed to assess whether the testing standard value was within the 95% confidence interval of median values. Paired *t*-tests were performed to compare the step lengths and left shoe–floor angles between the slippery trial and preceding dry trial in order to assess whether subjects anticipated the contaminant and changed their gait accordingly.

RESULTS

No significant differences were observed between the subjects' gait kinematics during the slippery trial before contacting the fluid contaminated tile and the preceding dry trial. Step length ($p = 0.088$, $t_{12} = -1.86$) and left shoe–floor angle ($p = 0.912$, $t_{12} = 0.11$) were not significantly different for subjects during the slippery trial and preceding dry trial. Step length mean (standard deviation) was 690 mm (67 mm) for the slippery trial and 710 mm (69 mm) for the preceding dry trial while shoe–floor angle at heel strike was 29° (5.3°) for the slippery trial and 28° (3.8°) for the preceding dry trial. Thus, there was no evidence to suggest that the subjects systematically altered their gait during the slippery trial as compared to the previous dry trial, which may imply that subjects were not anticipating the slippery condition. All parameters at all time points were normally distributed ($p > 0.05$) except for the lateral velocity angle at slip initiation ($W = 0.83$; $p = 0.014$). All subjects had slip distances that exceeded the 3-cm threshold and the PSS ranged from 0.79 to 2.58 m/s with an average of 1.72 m/s.

Shoe kinematics were substantially different at slip initiation than what is typically used according to common shoe testing standards (Fig. 3). At slip initiation, the average sagittal angle (14.7°) was larger than the 7° testing standard ($p = 0.002$, $t_{12} = 4.05$). The median lateral velocity angle of −66° was significantly different from the 0° testing standard ($p = 0.013$, $\textit{Signed-Rank}_{12} = -34.5$). The average sliding speed at slip initiation (0.27 m/s) was not significantly different from the testing standard (ASTM, 2011; International Standards Organization, 2012) of 0.3 m/s ($p = 0.586$, $t_{12} = -0.56$). At ½ PSS, none of the angles were significantly different from testing standards, although the sliding speed was significantly higher than that used in testing standards ($p < 0.001$, $t_{12} = 5.69$). Similarly, at PSS, the sliding speed was significantly higher than the testing standard ($p < 0.001$, $t_{12} = 7.22$); however, none of the angles were significantly different from the testing standards.

Of the 13 slips included in the analysis, subjects predominantly began slipping in a medial or medial/anterior direction ($n = 11$). Some of these subjects then continued to slip in a medial/anterior direction ($n = 3$;

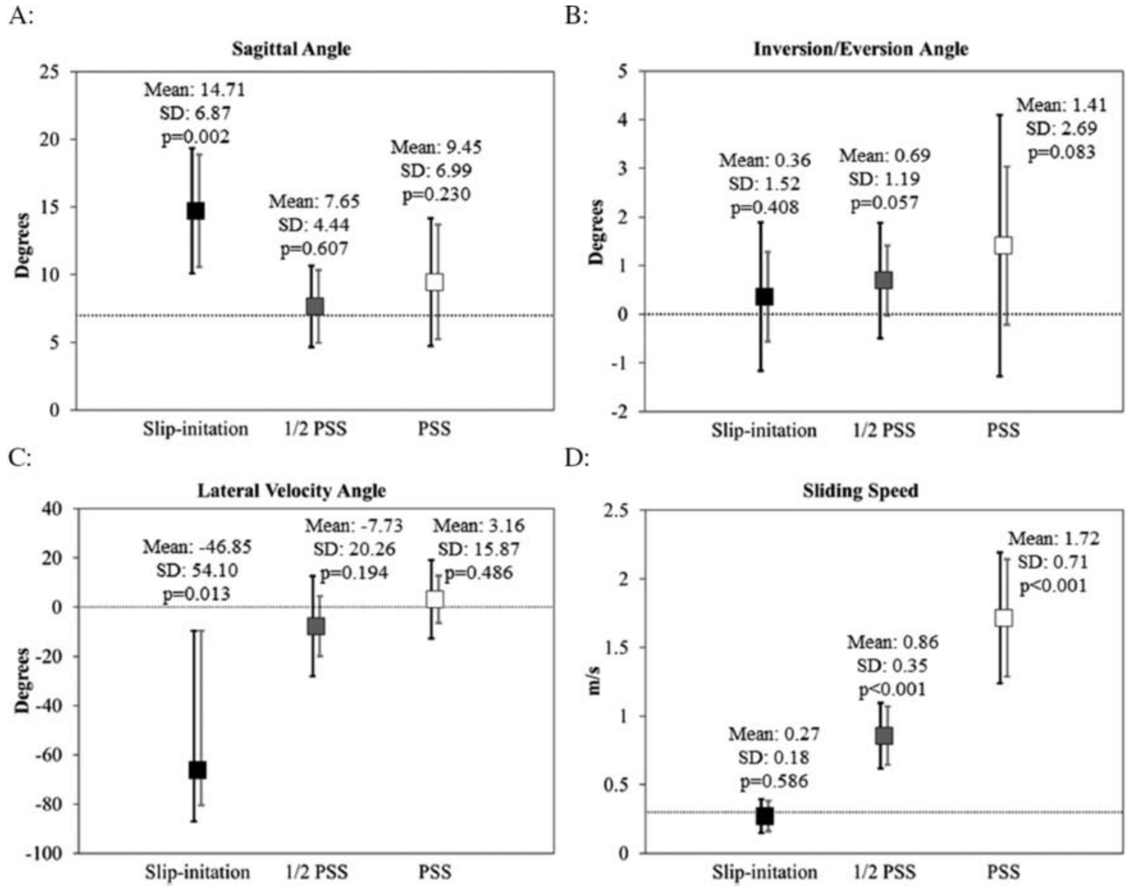

FIGURE 3 **(A) Sagittal shoe–floor angle, (B) inversion/eversion shoe–floor angle, (C) lateral velocity angle, and (D) sliding speed, for slip initiation (left), ½ PSS (middle), and PSS (right). For lateral velocity angle, positive values indicate a velocity vector pointing to the lateral aspect of the shoe and negative values indicate a velocity vector pointing to the medial aspect of the shoe. Horizontal black dotted lines represent the values used during standard shoe–floor friction testing methods. The gray error bars represent the 95% confidence interval for the mean and the black error bars represent the standard deviation in all cases except lateral velocity angle at the time of slip initiation. For lateral velocity angle at the time of slip initiation, the black bars represent the 95% confidence interval for the median and the gray bars represent the 25th and 75th percentile. The mean, standard deviation, and statistical significance for each parameter are located above the symbol and error bars at each time point.**

Fig. 4A), while others transitioned to slipping laterally and anteriorly ($n = 8$; Fig. 4C) before reaching PSS. The subjects that initially began slipping in a lateral/anterior direction ($n = 2$; Fig. 4B) continued to do so until PSS.

DISCUSSION

We found differences between the kinematics implemented during current shoe slip resistance testing standards and unexpected slips. In particular, the sagittal angles at the moment of slip initiation were found to exceed those used for testing methods. Also, the median sliding velocity at slip initiation was found to be directed medially suggesting slip resistance in the medial direction may be relevant in addition to testing in the anterior direction. At the other two time points (½ PSS and PSS), the sliding speeds were much higher than the 0.3 m/s typically used in testing standards. These findings call into question whether the testing conditions used during shoe–floor ACOF testing are biofidelic.

The shoe–floor angles at the time of slip initiation were between previously reported shoe–floor angles at heel strike and angles at the beginning of slipping. Previous studies have consistently reported shoe–floor angles of between 18° and 30° at the moment of heel strike (Strandberg & Lanshammar, 1981; Cham & Redfern, 2002b; Chambers et al., 2003; McGorry et al., 2008; McGorry et al., 2010). The reason shoe–floor angles in the present study (14.7°) are lower than shoe–floor angles at heel strike is because slip initiation occurs a short time after heel strike (Strandberg, 1983; Redfern et al., 2001). The shoe is quickly transitioning from an inclined angle (i.e., toe-up) to a foot flat position during the initial phase of stance (Redfern et al., 2001) and the delay between heel strike and slip

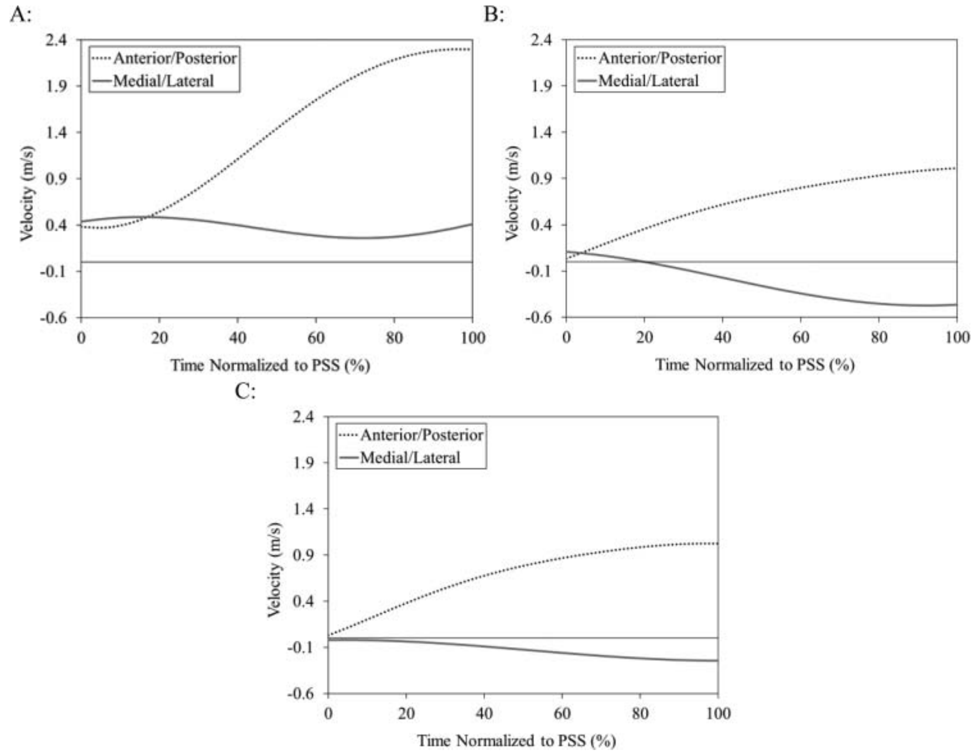

FIGURE 4 **Representative anterior/posterior (+anterior, dotted black line) and medial/lateral (+medial, solid gray line) velocities from slip initiation (0% of PSS) to PSS (100% of PSS) for (A) a subject that slipped only medially, (B) a subject that started slipping in the medial direction and then slipped in the lateral direction, and (C) a subject that slipped only laterally.**

initiation likely explains why our reported values are lower than previous reports for heel strike. The shoe–floor angles quantified in this study are likely higher than those previously reported—specifically 1.49° to 2.22° by Cham and Redfern (2002b) and 5.5° by Strandberg and Lanshammar (1981)—since these studies included data from trials where the subjects had previously experienced a slip. Subjects who are alert of the possibility of a slip or who are anticipating a slip are known to reduce the angle between their shoe and the floor (Cham & Redfern, 2002a; Chambers et al., 2003). The present study only used data from the first time subjects experienced a slip. Therefore, the estimates of sagittal angle at slip initiation in the present study are likely to be more indicative of the state of the shoe during an unexpected slip than these previous studies.

The sliding speed and sliding directions observed in this study provide an important clarification of the shoe kinematics during the early part of a slip. Previous work has found a posterior heel velocity followed by an anterior velocity—indicating that the shoe moved backward, stopped for an instant, and then slid forwards (Cham & Redfern, 2002b; McGorry et al., 2008; McGorry et al., 2010). When considering shoe velocity not just in the sagittal plane, the typical velocity pattern is a predominantly medial velocity (with a slight anterior or posterior component) followed by an anterior velocity. Furthermore, the average minimum speed between heel strike and PSS observed here was 0.3 m/s—indicating that there is not typically a moment where the shoe is static as suggested by previous research that shows a moment when the anterior/posterior velocity of the shoe is 0 (Cham & Redfern, 2002b; McGorry et al., 2008; McGorry et al., 2010). Thus, our study raises important questions regarding whether static friction or friction in the longitudinal direction are particularly relevant to slip-initiation.

Updating slip-testing guidelines to reflect the reality of slipping kinematics may better guide tread features that prevent slips. Previous research has indicated that tread orientation relative to sliding direction has an important impact on the ACOF between the shoe and floor surface. One study concluded that tread perpendicular to the sliding direction (Li & Chen, 2005) and another study concludedthat tread transverse (45°) to the sliding direction optimized the COF (Blanchette & Powers, 2015a). Both of these studies utilized testing protocols where the shoe moved straight forward. If the previous studies used sliding directions consistent with those found in the present study, it is likely that different optimal tread orientations would have been identified. Another tread feature that may not be appropriately measured using current testing methods is the beveled heel. In many shoe designs, the back of the heel is angled up, which improves contact area when the shoe is inclined (Lloyd & Stevenson, 1989). Differences in the sagittal angle used to test shoes and during a slip are likely to lead to beveled heel designs that are effective during testing but not during a slip. Increasing shoe angle has been found to decrease ACOF values, with approximately 20% reduction when increasing the angle from 10° to 20° (Beschorner et al., 2007), which indicates that measuring ACOF at a higher angle may yield values that are not comparable to data collected using current methods. The inconsistencies between observations from the current study and testing conditions in standard methods indicate that more scrutiny is needed regarding the ability of current testing methods to guide design of slip-resistant shoes.

The present study had a few limitations that should be acknowledged. We only considered a single type of footwear with a single flooring and contaminant. Footwear might be an important contributor to the shoe kinematics during slipping. In particular, other researchers have noted that non-traditional footwear (like clogs or sandals) alter the kinematics of gait (Chander et al., 2015). Also, certain kinetic measures that may be important to biofidelic slip-testing like normal force and center of pressure location were not considered in the present study. Future research should better clarify the central tendency and variability of these parameters at the moment of slip initiation in order to better inform slip-testing.

In conclusion, our results indicate that the sagittal angle and the slipping direction at the time of slip initiation differ from those used during standardized slip-testing methods. Making testing methods more biofidelic is likely to guide shoe design features that increase friction during actual slips. Thus, revisiting the testing kinematics used in slip-testing methods may be important for preventing slip and fall accidents.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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