Journal of Biomechanics 47 (2014) 458–463

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Fluid pressures at the shoe–floor–contaminant interface during slips: Effects of tread & implications on slip severity

Kurt E. Beschorner [a,*], Devon L. Albert [b], April J. Chambers [b], Mark S. Redfern [b]

[a] Department of Industrial Engineering, University of Wisconsin-Milwaukee, Milwaukee, WI 53201, United States
[b] Department of Bioengineering, University of Pittsburgh, Pittsburgh, PA, United States

ARTICLE INFO

Article history:
Accepted 31 October 2013

Keywords:
Slip and fall accidents
Fluid pressures
Reynolds equation
Shoe tread

ABSTRACT

Previous research on slip and fall accidents has suggested that pressurized fluid between the shoe and floor is responsible for initiating slips yet this effect has not been verified experimentally. This study aimed to (1) measure hydrodynamic pressures during slipping for treaded and untreaded conditions; (2) determine the effects of fluid pressure on slip severity; and (3) quantify how fluid pressures vary with instantaneous resultant slipping speed, position on the shoe surface, and throughout the progression of the slip. Eighteen subjects walked on known dry and unexpected slippery floors, while wearing treaded and untreaded shoes. Fluid pressure sensors, embedded in the floor, recorded hydrodynamic pressures during slipping. The maximum fluid pressures (mean+/−standard deviation) were significantly higher for the untreaded conditions (124+/−75 kPa) than the treaded conditions (1.1+/−0.29 kPa). Maximum fluid pressures were positively correlated with peak slipping speed ($r=0.87$), suggesting that higher fluid pressures, which are associated with untreaded conditions, resulted in more severe slips. Instantaneous resultant slipping speed and position of sensor relative to the shoe sole and walking direction explained 41% of the fluid pressure variability. Fluid pressures were primarily observed for untreaded conditions. This study confirms that fluid pressures are relevant to slipping events, consistent with fluid dynamics theory (i.e. the Reynolds equation), and can be modified with shoe tread design. The results suggest that the occurrence and severity of unexpected slips can be reduced by designing shoes/floors that reduce underfoot fluid pressures.

1. Introduction

Falling accidents account for 25% of non-fatal occupational accidents (U.S. Department of Labor-Bureau of Labor Statistics, 2012b), 14% of fatal occupational accidents (U.S. Department of Labor-Bureau of Labor Statistics, 2012a) and are the fastest growing source of workers' compensations claims (Liberty Mutual Research Institute, 2012). Slipping is the most common event leading to a fall (Courtney et al., 2001). A slip is initiated when the friction between the shoe and floor surface is insufficient to support the friction required for gait (commonly termed the required coefficient of friction) (Burnfield and Powers, 2006; Hanson et al., 1999). Footwear and tread has been identified as a risk factor for slipping in occupational settings (Bentley, 1998; Bentley and Haslam, 2001; Haslam and Bentley, 1999).

The available friction between the shoe and flooring are affected by several different factors including the shoe design (material and tread pattern) (Grönqvist, 1995; Li and Chen, 2004; Li et al., 2006b; Strobel et al., 2012; Redfern and Bidanda, 1994), the flooring design (material properties, roughness, waviness) (Chang et al., 2004, 2001b; Strobel et al., 2012; Redfern and Bidanda, 1994) and a liquid contaminant separating the surface (Beschorner et al., 2009, 2007; Chang et al., 2001a; Moore et al., 2012; Strobel et al., 2012). Tribological theory suggests that two different lubrication mechanisms contribute to slipping events: boundary lubrication (Moore et al., 2012; Strobel et al., 2012) and hydrodynamic lubrication (Beschorner et al., 2009, 2007; Chang et al., 2001a; Proctor and Coleman, 1988; Strandberg, 1985). In boundary lubrication, a fluid disrupts adhesion between a shoe and floor surface but does not affect the hysteresis between the surfaces (Strobel et al., 2012). In the presence of hydrodynamic effects (which occurs in the mixed, elastohydrodynamic and hydrodynamic lubrication regimes), fluid beneath the shoe–floor surface becomes pressurized and causes the shoe and floor surface to separate (Beschorner et al., 2009). This separation reduces interaction between the surfaces and can reduce the available friction to nearly zero (Beschorner and Singh, 2012). The Reynolds equation is the primary constitutive equation of the fluid pressures across the shoe–floor interface (Eq. (1)) and describes the interactions

---

[*] Correspondence to: University Services Research Building #201C, 115 E Reindl Way, Glendale WI 53212, United States. Tel.: +1 414 229 6403.
E-mail address: beschorn@uwm.edu (K.E. Beschorner).

0021-9290/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jbiomech.2013.10.046

between the variables: film thickness between the two surfaces, h, the fluid pressures, p, viscosity, η, entrainment velocities, v_x and v_y and squeeze of the surfaces, v_z (Hamrock et al., 2004). When applying the Reynolds equation to slipping, v_x is the shoe velocity towards the right side and v_y is the anterior shoe velocity. The form of Reynolds equation presented in Eq. (1) assumes that the floor is not moving, density of the fluid is constant and that the stretching of the shoe or floor surface is insignificant. The two main contributing factors to fluid pressures between shoe and floor surfaces are the wedge effect (Proctor and Coleman, 1988) and the squeeze film effect (Strandberg, 1985). The wedge effect describes the dependence of fluid pressures on the sliding velocity (v_x and v_y) and fluid viscosity (η), while the squeeze-film effect describes a reduction in fluid pressures over time. Previous modeling studies have shown that hydrodynamic pressures are typically centrally located near the trailing edge of the shoe surface (Beschorner et al., 2009). While hydrodynamic pressures, the wedge effect and the squeeze film effect have been suggested to contribute to slips with tribological theory and models, their presence has not yet been experimentally confirmed during real slip events.

$$\frac{\partial}{\partial x}\left[\frac{h^3}{12\eta}\frac{\partial p}{\partial x}\right]+\frac{\partial}{\partial y}\left[\frac{h^3}{12\eta}\frac{\partial p}{\partial y}\right]=\frac{v_{x(shoe)}}{2}\frac{\partial h}{\partial x}+\frac{v_{y(shoe)}}{2}\frac{\partial h}{\partial y}+v_z \qquad (1)$$

Shoe tread is intended to prevent the build-up of hydrodynamic pressures by providing channels that allow the fluid to escape from between the shoe–floor interface (Strandberg, 1985; Tisserand, 1985). Experimentally, increased tread width (Li and Chen, 2004) and tread depth (Li et al., 2006a) have been associated with higher available friction values. Other experimental studies, however, have found inconsistent relationships between shoe tread depth and available coefficient of friction (Blanchette and Powers, 2012). Previous work by our research group has revealed that untreaded shoes are associated with high hydrodynamic pressures and low coefficient of friction values (Beschorner and Singh, 2012). The effects of shoe tread on hydrodynamic pressures and slip outcomes during real slipping events is still not well understood.

The purpose of this study was to observe hydrodynamic pressures during slipping and to determine how fluid pressures affect the severity of a slip. The impact of the presence versus absence of tread on this relationship also was investigated. Correlations between fluid pressures and the instantaneous sliding speed, medial–lateral position on the shoe surface and position of the sensors relative to the walking direction were compared with the expected trends based on tribological theory.

2. Methods

Eighteen subjects between the ages of 20 and 33 years old were recruited to participate in the study (10 female, mean ± standard deviation: age 23.5 ± 4.0 years, height 1.71 ± 0.072 m, weight 70.0 ± 11.8 kg), which was approved by the University of Pittsburgh Institutional Review Board. Only healthy subjects without significant musculoskeletal or neurological disorders were included. All subjects provided informed consent prior to data collection.

Fig. 1. Picture of the fully treaded shoes (left) and the untreaded shoes that had the tread fully removed (right).

Participants performed two sets of walking trials, both of which concluded with an unexpected slip. Participants wore fully treaded shoes during one slip and untreaded shoes during the other slip. The shoes were made of a rubber compound (Shore A Hardness: 58) and were advertised as being slip-resistant (Fig. 1). The treaded shoes had a tread depth of 2.4 mm, a tread width of 5 mm and a tread channel width of 2.4 mm, while the untreaded shoes had the tread completely removed from the shoe sole (Fig. 1). An abrasion process was used to remove the tread using 80 grit sand paper similar to standard testing methods for shoe wear (International Standards Organization, 2012). The order in which the shoes were introduced was randomized. Slips were induced with a 90%:10% glycerol:water solution (viscosity: 219 cP) that was spread evenly across a 610 × 610 mm floor surface. Prior to each slip, participants performed 5–8 baseline dry trials. During the baseline dry trials, the participants' starting position was adjusted so that their heel hit directly behind an array of fluid pressure sensors. Participants listened to music and faced the wall between each trial to reduce their awareness that a fluid contaminant had been placed on the floor, similar to previous studies that have achieved unexpected slips (Beschorner et al., 2013; Chambers and Cham, 2007; Moyer et al., 2009, 2006). The lights were dimmed to obscure the condition of the floor. Subjects were made aware during the informed consent process that they might experience a slippery floor at some point but were not informed of the location, nature or timing of the slippery surface. Subjects' pressure data were analyzed only if they either stepped directly on the fluid pressure sensor array or if they slipped across the array. A subject was considered to have stepped or slid on a fluid pressure sensor if a marker placed on the subject's heel passed within the boundaries of the sensor array during the slip. The heel marker was used instead of other foot markers because previous studies have indicated that the foot is inclined at the start of an unexpected slip and that the heel portion of the shoe is in contact with the floor throughout the slip (Cham and Redfern, 2002a, 2002b). Eleven of eighteen slips with untreaded shoes and six of eighteen slips with treaded shoes met these qualifications and were included in the analysis. Peak slipping speed was only calculated when the subject stepped cleanly on the glycerol-covered area.

The instrumentation included an array of fluid pressure sensors and a reflective marker placed posteriorly and inferiorly on the heel. A 3 × 3 array of fluid pressure sensors were embedded beneath the floor surface to measure hydrodynamic pressures as the participants slipped across the floor surface (Fig. 2). The fluid pressure sensors were spaced 30 mm apart from each other in both directions. The pressure sensors (Gems® 3100-R-150PG-08-F-X-3) had an inlet diameter of 4 mm, accuracy of 2.5 kPa and range of 1000 kPa. When the fluid contaminant was applied to the floor, the inlet of each pressure sensor was filled completely with fluid to ensure continuous fluid from the transducer to the top of the floor surface. Similar methods have been used to evaluate shoes using a slip-tester (Beschorner and Singh, 2012) and in evaluating the tribology of chemical mechanical polishing (Shan et al., 2000). A marker was placed on the inferior portion of the heel in order to track the slipping kinematics. Marker position was tracked with a 14 camera motion capture system (Vicon MX). The system was calibrated to achieve an accuracy of within 1 mm.

The fluid pressures were characterized using the magnitude of the fluid pressures and the duration in which the pressures exceeded baseline levels. Fluid pressures were typically characterized by a single peak (Fig. 2) and the maximum of that peak was identified. Fluid pressure duration was defined as the time between the first and last moment that fluid pressures exceeded 5 standard deviations of baseline levels. Typical baseline standard deviation pressures were around 0.24 kPa. The severity of the slip was characterized using peak slipping speed (PSS), which was defined as the peak resultant speed during the slip (Moyer et al., 2006). In order to accomplish the secondary objective of determining the effects of the instantaneous slipping speed and the medial/lateral position relative to the shoe, the spatiotemporal variables of the foot relative to each individual fluid sensor were calculated. The instantaneous resultant slipping speed (IRSS) was calculated at the time that the heel passed each of the fluid pressure sensors. IRSS was used for this analysis instead of the peak sliding speed because IRSS relates to the state of the shoe when the heel was over the sensor and is therefore more relevant to how shoe kinematics influence the fluid pressures observed in a given sensor. The medial–lateral distance between the heel marker and the fluid pressure