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Worn Region Size of Shoe Outsole Impacts Human Slips: Testing a Mechanistic Model

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Abstract

Shoe outsole tread wear has been shown to increase slip risk by reducing the tread's ability to channel fluid away from the shoe-floor interface. This study establishes a connection between geometric features of the worn region size and slipping. A mechanistic pathway that describes the relationship between the worn region size and slip risk is assessed. Specifically, it is hypothesized that an increased worn region size leads to an increase in under-shoe fluid pressure, which reduces friction, and subsequently increases slipping. The worn region size, fluid pressure, and slip outcome were recorded for 57 participants, who were exposed to an unexpected slip condition. Shoes were collected from each participant and the available coefficient of friction (ACOF) was measured using a tribometer. A greater shoe worn region size was associated with increased slip occurrence. Specifically, a 1 mm increase in the characteristic length of the worn region (geometric mean of its width and length) was associated with an increase in slip risk of ~10%. Fluid pressure and ACOF results supported the mechanistic model: an increase in worn region size correlated with an increase in peak fluid pressure; peak fluid pressures negatively correlated with ACOF; and increased ACOF correlated with decreased slip risk. This finding supports the use of worn region size as a metric to assess the risk of slipping.

Keywords

Slips; trips; and falls; Hydrodynamic lubrication; Footwear

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Conflict of interest statement

There are no known conflicts of interest among the authors of this manuscript.

Introduction

Workplace falls represent 27% of nonfatal occupational injuries (U. S. Department of Labor-Bureau of Labor Statistics, 2019) with approximately 40–50% of these falls initiated by a slip (Courtney et al., 2001). The frequency of slips in the workplace has been shown to be dependent on the type of footwear (slip resistant versus non-slip-resistant) and slipping is more frequent as shoes become worn (Verma et al., 2014). However, evidence is still emerging regarding the mechanisms by which footwear and wear influences slipping risk.

The friction between the shoe and floor can be used to determine the risk of experiencing a slip. In particular, higher available coefficient of friction (ACOF) between the shoe and the floor surface (Beschorner et al., 2016; Burnfield and Powers, 2006; Iraqi et al., 2018) relative to the frictional requirements of gait (i.e. the required coefficient of friction, RCOF) is predictive of reduced slipping (Hanson et al., 1999). Shoe-floor-contaminant friction is influenced by two lubrication phenomena: boundary lubrication (Moghaddam et al., 2018; Shibata, 2019; Strobel et al., 2012; Yamaguchi et al., 2017) and mixed-lubrication (Beschorner et al., 2014; Hemler et al., 2019; Proctor and Coleman, 1988; Singh and Beschorner, 2014). Boundary lubrication is the lubrication region that describes the disruption of adhesion between the shoe and floor surfaces by a liquid contaminant. An increase in fluid pressure between the shoe and floor surface indicates a transition from a boundary lubrication to mixed-lubrication (Beschorner et al., 2009; Chang et al., 2001; Moore et al., 2012), which leads to a decrease in friction. This study aims to determine the relationship and mechanism by which outsole features, specifically the wear characteristics, influence slipping.

Two hydrodynamic phenomena contribute to the development of hydrodynamic pressures and fluid film thickness between shoe and floor surfaces: the wedge effect and squeeze-film effect (Beschorner et al., 2007; Chang et al., 2001; Singh and Beschorner, 2014). The wedge effect leads to an increase in hydrodynamic effects when two surfaces move relative to each other and entrain fluid into a narrowing gap between the surfaces (Hamrock et al., 2004). The squeeze-film effect is caused by the pressure required to transport fluid from between two converging surfaces (driven by Poiseuille flow mechanics) (Hamrock et al., 2004). Shoe tread channels relieve the fluid pressure by providing a low-resistance path for fluid flow (Singh and Beschorner, 2014; Strandberg, 1985; Tisserand, 1985). Bearing theory further explains the relationship between shoe regions that lack tread and the resulting hydrodynamics. The fluid film thickness (Fuller, 1956) and the mean pressure (Fuller, 1956; Hamrock et al., 2004) under a bearing are highly sensitive to the size of the bearing based on solutions to 3D inclined bearings, 2D inclined bearings, and 2D stepper bearings. As a result, it is reasonable to suspect an increase in hydrodynamic pressures and slip risk with a larger worn region size. Previous research has found that artificially worn shoes have higher under-shoe fluid pressures than new shoes (Beschorner et al., 2014). Previous research has also demonstrated that the worn region size is associated with an increase in under-shoe fluid pressures and a decrease in ACOF based on mechanical experiments (Hemler et al., 2019; Hemler et al., 2020). While these prior studies presented important new information for characterizing the impact of shoe wear on slipping, three important gaps in the literature remain: 1) the impact of the worn region size on human slips; 2) validating the influences of wear on increased under-shoe fluid pressures and reduced ACOF in the context of human slips; and 3) confirming the impacts of tread wear on slipping in naturally-worn shoes.

The purpose of this study is to determine if an increased size of a shoe's worn heel region increases slipping (Hypothesis 1, H1). In the current study, the mechanistic pathway for this potential relationship is empirically tested using a model wherein the hypotheses build upon the results of previous works and theory (H2–H4 in Fig.1). The size of the worn region is hypothesized to increase fluid pressures (H2). Increased fluid pressure is hypothesized to decrease ACOF (H3). The reduced ACOF is then hypothesized to increase slip risk (H4). Although the literature does not directly connect the size of the worn heel region to slip outcome, several studies support the rationale behind these hypotheses. 1) Beschorner et al. (2014) found a reduction of slip severity and under-shoe fluid pressures for fully treaded shoes relative to worn shoes, which serves as the rationale for H1 and H2. 2) Hemler et al. (2019) artificially wore down the sole of slip-resistant shoes to measure the change in ACOF and under-shoe hydrodynamic pressures justifying H2. This study found a positive association between worn region and fluid pressure and a negative association between worn region and ACOF, which is the basis for H3 (Hemler et al., 2019). 3) Iraqi et al. (2018) found that a decrease in ACOF leads to an increases slip risk, which is supported by previous research in support of H4 (Burnfield and Powers, 2006; Hanson et al. 1999).

Methods

This observational, cross-sectional study measured under-shoe fluid pressure and slip risk during a single testing session, while participants wore their own, naturally worn shoes. The participants were full-time workers and donned their work shoes during the study. Participants completed a series of walking trials ending with an unexpected slip trial while wearing their shoes (Fig.2A). During the unexpected slip trial, participants were aligned to step over a contaminant-covered array of fluid pressure sensors (Fig.2B) and slip outcome was determined. The worn heel region size (Fig.3) was measured for each shoe, and each shoe was also tested on a portable slip tester to determine the ACOF.

Participants

Fifty-seven participants (mean age: 34±13 years, mean height: 169.7±9.5 cm, mean weight: 79.4±17.8 kg, 25: 28 female: male) were analyzed from a cohort of 90 recruited participants. Participants were excluded if they reported being aware of the contaminant prior to stepping on it (n = 9); they did not step on the fluid pressure sensors in the floor during the slip trial (n = 16); their shoe tread were clogged with substances such as food (n = 1); or their shoes had holes in the outsole (n = 5). Participants also agreed to forfeit their shoes. The eligibility criteria included an age between 18 and 65 years, a BMI less than 35 kg/m^2, wearing the same closed-toed, flat, and intact shoes at least 5 days a week, and no major musculoskeletal or neurological medical conditions. Participants who worked at least 30 hours per week in any industry sector were recruited for the study. Of those included, 20 shoe pairs were reported to be worn less than 6 months, 23 worn between 6–12 months, and 10 shoes were worn greater than 12 months. Thirty-two shoes were designated by the manufacturer as slip resistant (SR) and twenty-one shoes were not slip resistant (NSR). The procedures were approved by the University of Pittsburgh Institutional Review Board (#PRO15030214) and all participants signed an informed consent form.

Experimental Setup and Procedure

Prior to data collection, participants donned tight-fitting clothes and their personal shoes. Seventy-nine reflective markers were placed on bony landmarks of interest to track the participant's motion during each trial using a motion capture system (Fig.2A) (Moyer, 2006).

Participants completed a series of walking trials based on similar methods used by Beschorner et al. in a study that examined the influence of tread on fluid pressure and its correlation with slip severity (2014). During the baseline (without contaminant) walking trials preceding exposure to the contaminant, the participants were aligned to ensure foot strike on two force plates (Bertec 4060A, Columbus, OH) until 5 clean strikes per shoe were recorded. The forces were used to quantify required coefficient of friction (RCOF). The participants' starting point was then adjusted to align step position with the 30-fluid pressure sensor array (Fig. 2B), which was embedded in a floor tile. This tile was encountered by the participant about one step before the first force plate. The contaminant (100mL of a 90% glycerol-10% water by volume solution) was poured across the sensor array to completely cover all sensors; this process was completed while the participant was distracted. The participant was instructed to face away from the walking path, while listening to music and completing a puzzle for one minute before each walking trial. This distraction task along with dimmed lighting was intended to reduce participants' awareness of the liquid contaminant placed on the floor during the unexpected slip trial. Marker data were collected at 120 Hz. Ground reaction forces and fluid pressures were collected at 1080 Hz.

Data Analysis for Human Testing

Ground reaction forces from the five baseline dry walking trials were used to calculate the RCOF, defined by the ratio of the shear force to the normal force. The shear force was defined as the resultant magnitude of the horizontal ground reaction forces and the normal force was defined as the vertical ground reaction force (Beschorner et al., 2016; Beschorner et al., 2019; Iraqi et al., 2018). The peak of the RCOF time series was calculated during weight acceptance criteria based on normal force magnitude, shear force direction, time, and slope consistent with previous research methods (Beschorner et al., 2016; Beschorner et al., 2019; Chang et al., 2011; Iraqi et al., 2018). The average of the peak RCOF values from the five baseline dry trials was used for the analysis.

The coordinates of the heel marker (located at the most inferior position of the posterior section of the shoe), Figure 2A, were recorded to identify the initial heel contact location during the unexpected slip trial (Albert et al., 2017; Beschorner et al., 2016; Jones et al., 2018). The peak fluid pressure value was determined as the maximum pressure across all 30 sensors (Fig. 2C). The location of the slip relative to the fluid pressure sensor array was assessed to determine if the foot slipped across the pressure sensor array; fluid pressure data was excluded if the foot did not contact the floor within this region.

The peak slip speed (PSS) was also quantified from the human gait data. The resultant speed of the heel marker was calculated using two-time step differentiation (Cham and Redfern, 2002) based on both the anterior-posterior and medial-lateral components. PSS was calculated as the first local maximum heel speed that occurred at least 50 ms after heel contact (Moyer et al., 2006). A participant was considered to have slipped if the PSS exceeded 0.2 m/s. This cutoff was established *a priori* (prior to data collection) based on previous data showing a bimodal distribution of low-severity slips for treaded slip-resistant shoes below this value and high severity slips for fully worn shoes above this value (Beschorner et al., 2014). All kinematic data were filtered with a 4th order, low-pass Butterworth filter using a 24 Hz cutoff frequency (Iraqi et al., 2018).

Footwear Characterization

The worn heel region size was determined by measuring the length and width of the worn heel region relative to the long axis of the shoe (Fig. 3). The length was defined as the longest anterior-posterior length of the largest continuous section on the shoe heel outsole (Hemler et al., 2019). The maximum allowable wear length was 50 mm for completely worn shoes since previous research has shown that fully worn shoes tend to only experience fluid pressures in the posterior 50 mm of the shoe (Singh and Beschorner, 2014). The width was the maximum medial-lateral dimension of the worn region.

Shoe-Floor ACOF Testing Procedure

ACOF was recorded for the shoes using the portable slip simulator (Aschan et al., 2005; Chanda et al., 2018; Iraqi et al., 2018; Jones et al., 2018). The shoes that contacted the slippery contaminant (all right shoes except one left shoe) were tested. The shoes were tested against the same flooring (laminate) and contaminant (90% glycerol) as the unexpected slip trial. Test conditions included a normal force of 250 N, sliding speed of 0.5 m/s, and shoe-floor angle of 17° (Iraqi et al., 2018; Iraqi et al., 2020; Jones et al., 2018). These test conditions have been determined to be relevant to slipping biomechanics (Albert et al., 2017; Iraqi et al., 2018) and predictive of slip outcomes (Iraqi et al., 2018). Shear and normal forces were recorded with a force plate (Bertec FP4060, Columbus, OH) at 500 Hz and ACOF was calculated as the ratio of shear to normal force over a 200 ms period. The ACOF was averaged across five repeated trials. Between each trial, the contaminant was redistributed to cover the surface.

Statistical Analysis

A series of regression analyses was performed to assess the impact of the size of the worn region on slip outcome and evaluate the proposed mechanistic model Table 1. To analyze Hypothesis 1, two logistic regression analyses were performed using slip outcome as the dependent variable with worn region size as the independent variable. A univariate model and a multivariate model were performed with the multivariate model including individual RCOF and the slip-resistant shoe category as covariates. The mechanistic model (described by Hypotheses 2–4) was tested via three regression models. To test Hypothesis 2, a regression model was performed to determine the effects of the worn region size (independent variable) on fluid pressures (dependent variable) with slip-resistant shoe category and its interaction with worn region size as covariates. Hypothesis 3 was tested with a regression model to determine the influence of fluid pressure (independent variable) on ACOF (dependent variable), with slip-resistant shoe category and its interaction with fluid pressure as model covariates. Finally, to test Hypothesis 4, the effect of ACOF on slip outcome was tested with a logistic regression analysis, while controlling for RCOF. Inclusion of slip-resistant shoe category and RCOF as covariates was based on previous research that shows these variables are relevant to slip risk (Verma et al., 2014; Beschorner et al,. 2016). Peak pressure values and shoe wear were square-root transformed to satisfy normality and linearity assumptions. All analyses used a significance level of 0.05 and were completed using statistical software (JMP, SAS Corp., NC). All statistical analyses (including the covariates but excluding the transformations) were designed prior to performing statistical analyses on this dataset.

Results

H1: Worn Region - Slip Outcome:

The mean worn region size (mean ± standard deviation) varied across the shoes (all shoes: 1290 ± 1240 mm^2; SR shoes: 760 ± 910 mm^2; NSR shoes: 2200 ± 1220 mm^2). Slips were observed for 41 participants (71.9%). Slipping increased with the size of the worn region size for both the multivariate and univariate analyses (multivariate: $\chi^2_{(1)} = 4.2$, $p = 0.040$; univariate: $\chi^2_{(1)} = 20.6$, $p < 0.001$) (Fig.4). Specifically, for every 1 mm increase in the characteristic length of the worn region (i.e., square root of worn region size), the odds of slipping increased by 8.6% for the multivariate model and by 11.6% for the univariate model. Neither RCOF nor slip-resistant shoe category significantly influenced slip risk (Supplemental Table 1).

H2: Worn Region - Fluid Pressure:

The peak hydrodynamic pressure for all shoes, SR shoes, and NSR shoes was 140.1 ± 161.8 kPa, 99.7 ± 148.1 kPa, and 209.3 ± 164.2 kPa, respectively. The size of the worn region was positively correlated to peak fluid pressure ($F_{1,53} = 10.1$, $p = 0.003$) (Fig.5). Slip resistance category (SR vs. NSR) and its interaction with worn region size did not influence fluid pressures (Supplemental Table 2).

H3: Fluid Pressure - ACOF:

The measured ACOF values for all shoes, SR shoes, and NSR shoes were 0.124±0.069, 0.153 ± 0.065, and 0.077 ± 0.044, respectively. Peak pressures were significantly associated with decreased ACOF ($F_{1,53} = 24.3$, $p < 0.001$) (Fig.6). In addition, SR shoes had a higher ACOF than NSR shoes (Supplemental Table 3). The relationship between fluid pressure and ACOF was not influenced by the slip resistance category of the shoe (i.e., no interaction effect was observed) (Supplemental Table 3).

H4: ACOF - Slip Outcome:

An increase in ACOF was associated with a reduction in slips ($\chi^2_{(1)} = 15.3$, $p < 0.001$). An increase in ACOF of 0.01 was associated with a 21% reduction in chance of slipping odds (Fig.7). Increased RCOF was associated with an increase in slipping (Supplemental Table 4).

Discussion

The results show a positive correlation between the heel worn region size and slip outcome as well as support for the proposed mechanistic model. Specifically, a larger worn region size was associated with higher fluid pressures, which were associated with reduced ACOF. These lower ACOF values were associated with increased likelihood of a slip. Although SR shoes typically had smaller worn regions than NSR shoes, the trends for increased hydrodynamic pressure and slip outcome were observed even when controlling for the slip-resistant shoe category. Importantly, this study demonstrated these trends across a wide range of shoe ages and both slip resistant categories.

The finding that the hydrodynamic pressure increased with an increase in worn region size is consistent with expectations that shoe tread channels mitigate under-shoe fluid pressure and reduce slip risk (Beschorner et al., 2014). The correlation between worn region size and fluid pressure is also consistent with tribology theory; a large worn region size leads to longer pathways for fluid to flow in order to reach the outside of the contact region (Fuller, 1956; Hamrock et al., 2004). Additionally, the results of this study support previous studies that found a decrease in ACOF values with higher peak fluid pressures, resulting in an increased chance of slipping (Beschorner et al., 2009; Singh and Beschorner, 2014). This increase in fluid pressure causes an increased separation between the shoe and the floor surface, leading to a decrease in ACOF (Fig.6) (Hamrock et al., 2004). Lastly, the relationship between ACOF and slip risk is consistent with previous research that has consistently demonstrated this empirical relationship especially when RCOF is considered (Beschorner et al., 2016; Burnfield and Powers, 2006; Hemler and Beschorner, 2017; Iraqi et al., 2018).

This study has important occupational and public safety implications. The size of the worn region at the heel is an important parameter to monitor when considering whether worn shoes should be replaced. Worn shoes become less safe as this region becomes larger. Also, a large spread was observed in the size of the worn region and hydrodynamic pressures for each shoe age group (Fig.5). This may indicate that relying on workers' recollection of shoe age may not be as predictive as actual measurements of the worn shoe condition. This empirical relationship can guide a worker's decision to replace worn shoes by tracking the size of the worn region. For example, the size of the worn region can be compared with a common object (e.g., a AAA or AA battery) to guide when shoes reach a wear level that justifies replacement.

Certain limitations should be acknowledged in this study. First, only a single flooring and lubricant were considered. Previous research has demonstrated a non-linear relationship between flooring topography and under-shoe fluid pressures (Iraqi, 2013); however, the interaction between flooring and the worn region on under-shoe hydrodynamics remains largely unknown. While only a single lubricant was considered, hydrodynamic models predict that fluid pressures should scale linearly with viscosity (Hamrock et al., 2004). Thus, higher viscosity contaminants would likely amplify the effects of worn region size on fluid pressures and reduction in ACOF. Lastly, the study utilized a single walking task in a laboratory environment. Confirming the relationship between worn region size and slip risk in authentic occupational environments would confirm the relevance of this parameter to occupational safety programs.

Conclusion

This study highlights the importance of monitoring worn heel region size to mitigate slip risk. The hypotheses (H2–HH4) for the mechanistic pathway were supported, consistent with theoretical expectations (Beschorner et al., 2009; Beschorner et al., 2014; Beschorner et al., 2016; Beschorner and Singh, 2012; Burnfield and Powers, 2006; Hemler et al., 2019; Iraqi et al., 2018). A larger worn region in the heel increased peak fluid pressure leading to a decrease in ACOF, which correlated to increased slip risk. The correlation between a larger worn heel region and higher slip risk demonstrates the utility of using worn region for making shoe replacement decisions. As such, the results support the use of worn region size to identify shoes in need of replacement and thus reduce occupational injuries related to slipping.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgements

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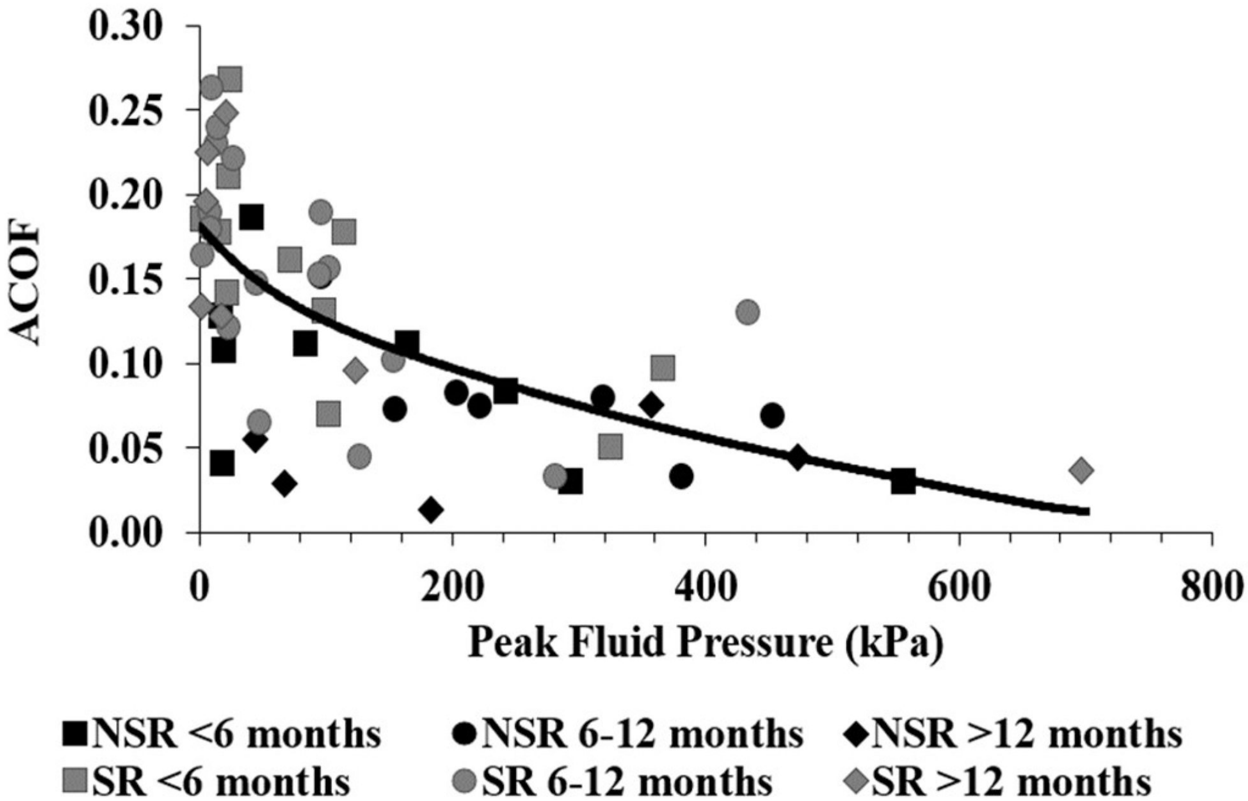

Figure 1.

The proposed mechanistic model is described by the worn region influencing fluid pressures, which influence ACOF (blue/gray boxes). This pathway is hypothesized to explain the impact of the worn region on slip outcome. Specific hypotheses (black boxes) explore this model at each step.

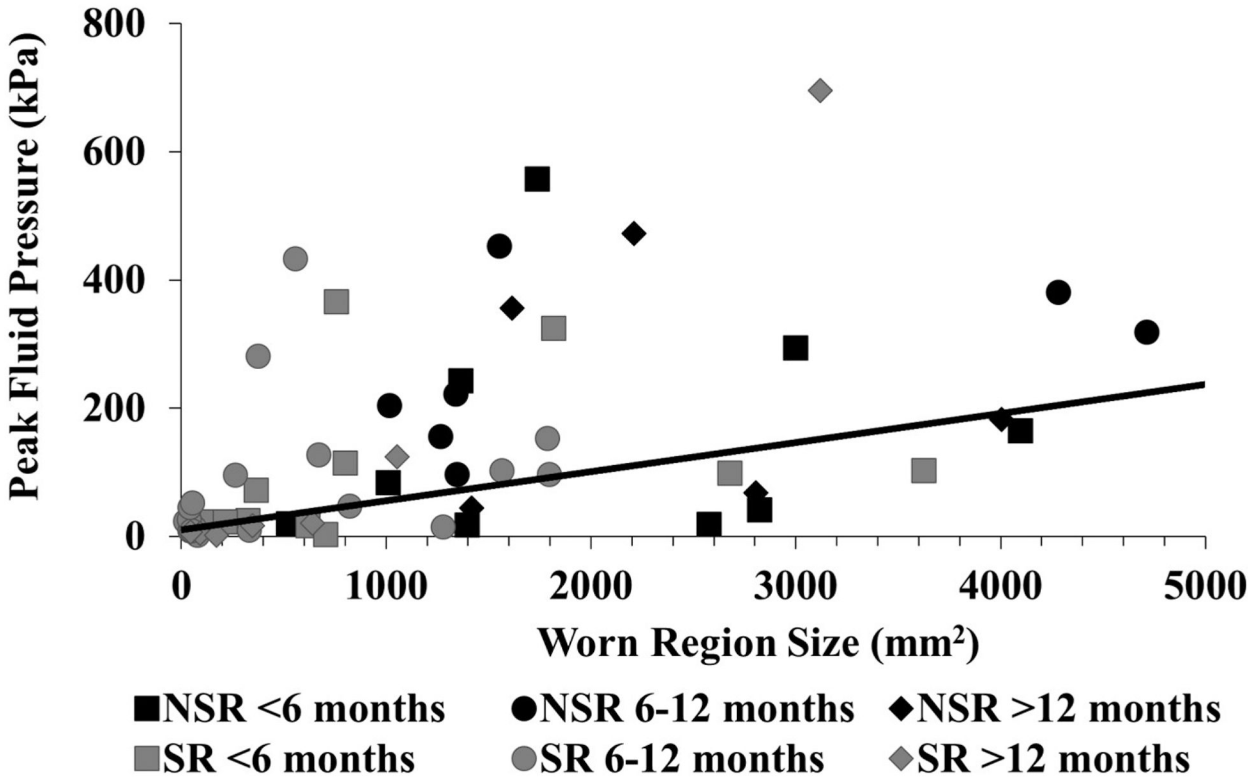

Figure 2.

A: The experimental setup for exposing participants to slippery conditions. The cameras surrounding the gait testing area collected the position of the reflective markers. The force plates, fluid pressure sensor array, and harness are labeled. B: The heel marker was used to assess slipping, including the slip trajectory (blue line) as the foot crossed the fluid pressure sensor array covered in a liquid contaminant. Sensors are numbered by row then column. C: The fluid pressure data from the 30 sensors (numbered above each plot) were used to find the maximum pressure value ("Max").

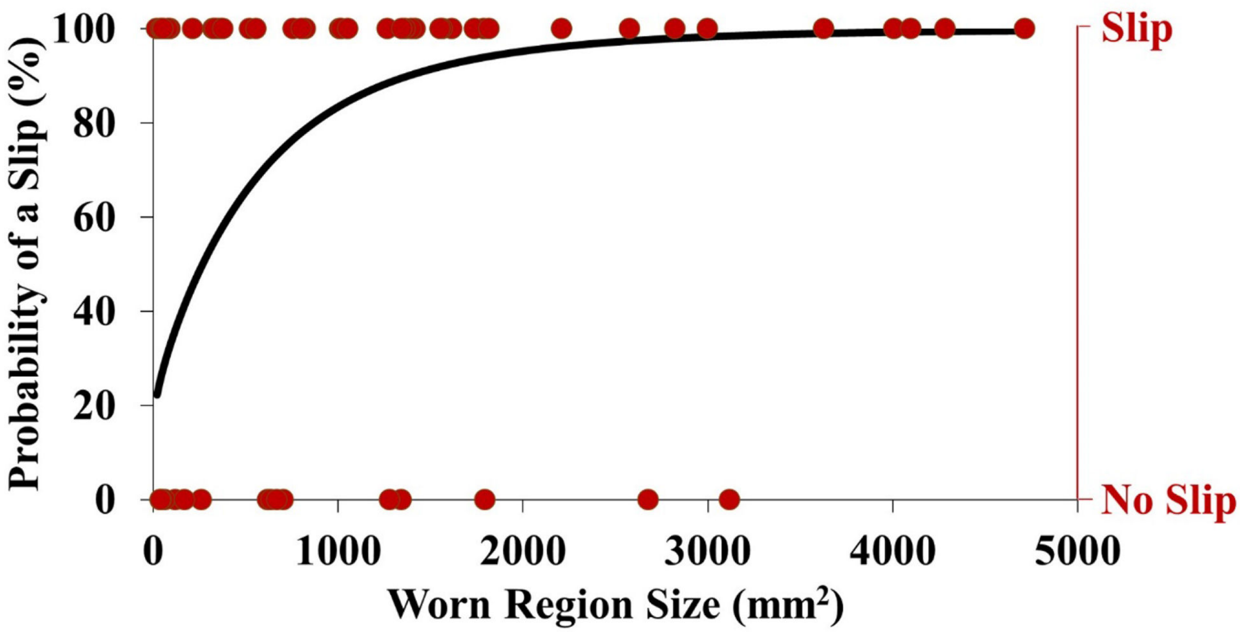

Figure 3.
Examples of shoes and the worn region size included in the study. Shoe A is an NSR shoe with a moderate worn region size and Shoe B is a SR shoe with a smaller worn region size. The yellow arrows indicate the length and width of the worn region size that was measured.

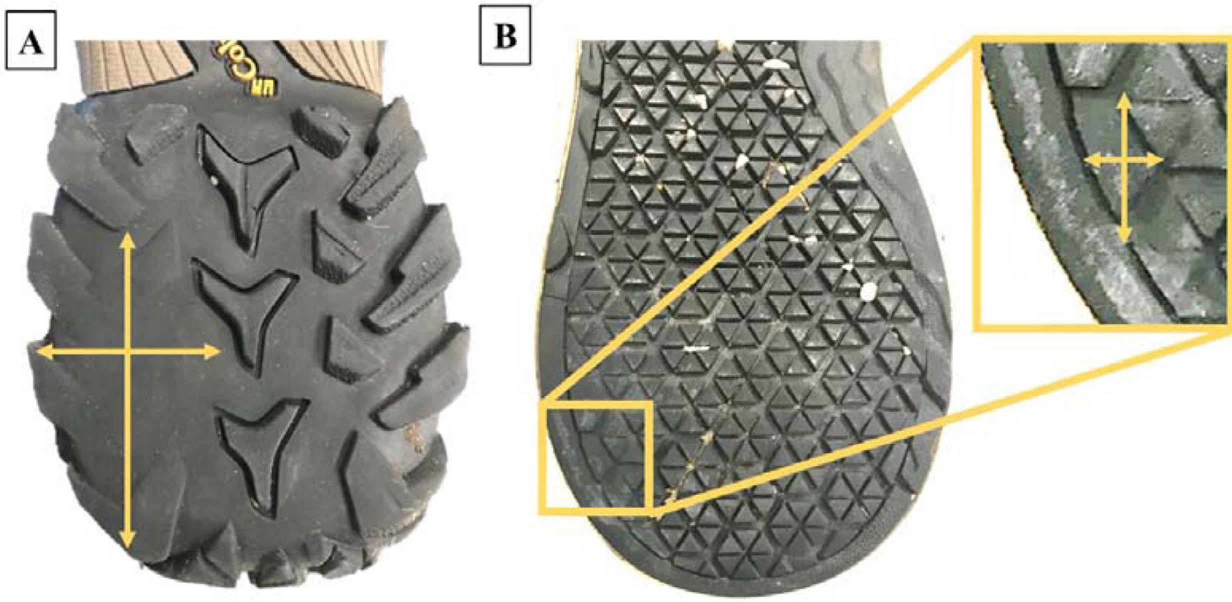

Figure 4.

The predicted probability of a slip (solid black line) and the measured slip outcomes (circles) based on the worn region size for all included participants. The predicted line was computed using the model fit for the univariate model (H1B).

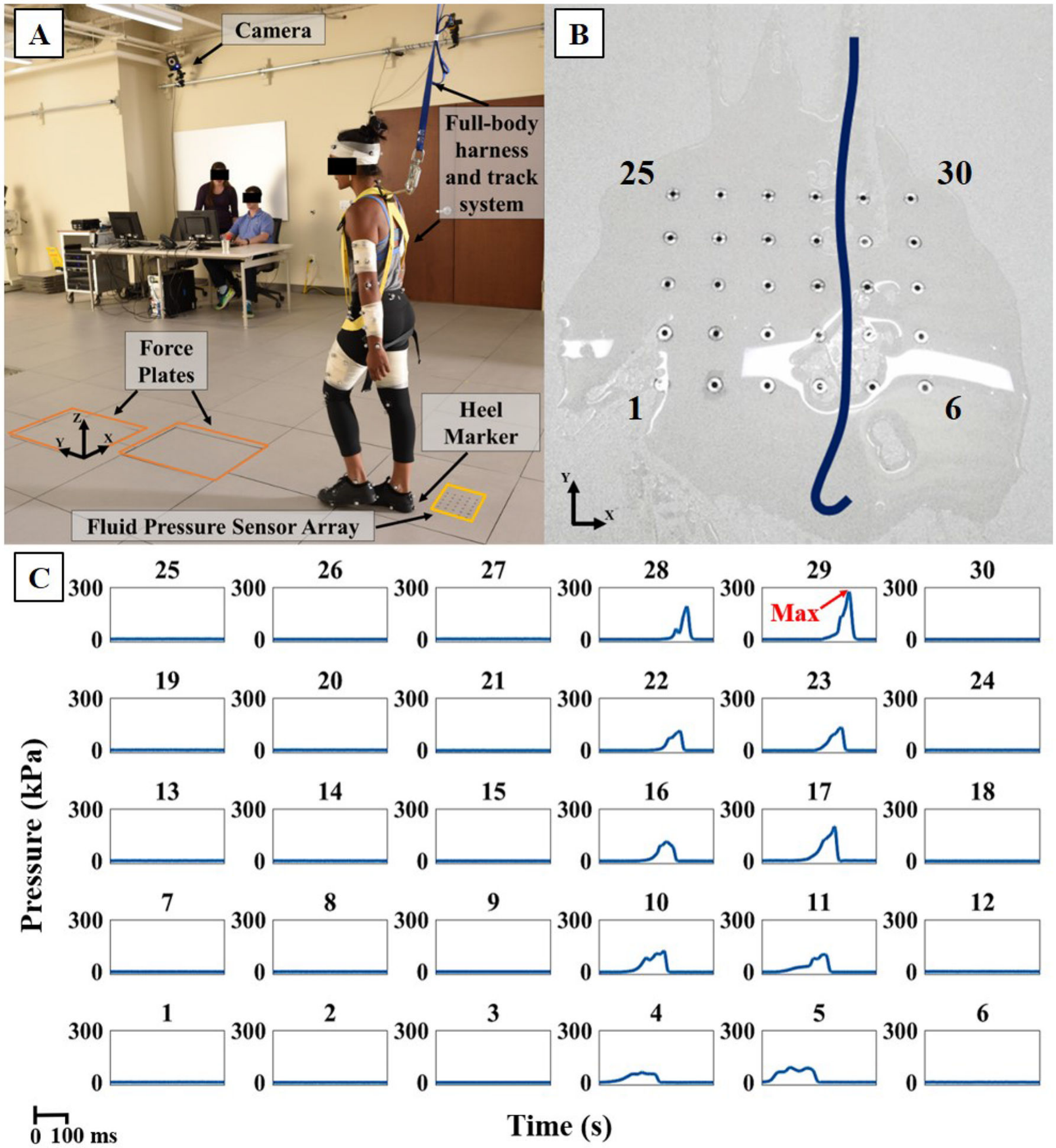

Figure 5.

Results from Hypothesis 2: The effect of worn region size on peak fluid pressure. The black lines show the regression fit line. Different markers represent different slip-resistant categories and shoe age.

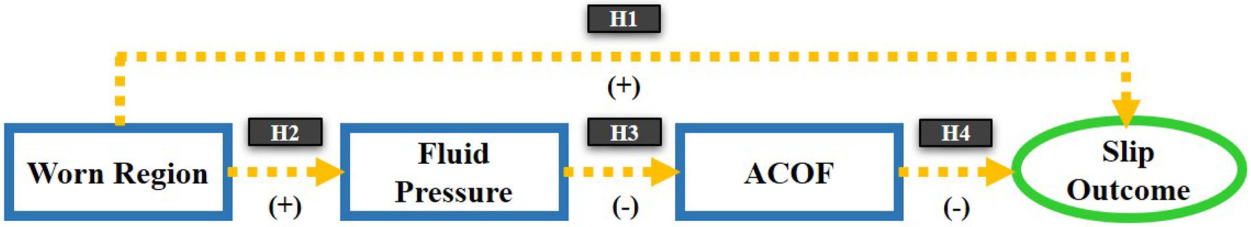

Figure 6.

Results from Hypothesis 3: a negative correlation ($p < 0.001$) was observed between peak fluid pressure and ACOF. Different markers represent different slip-resistant categories and shoe age.

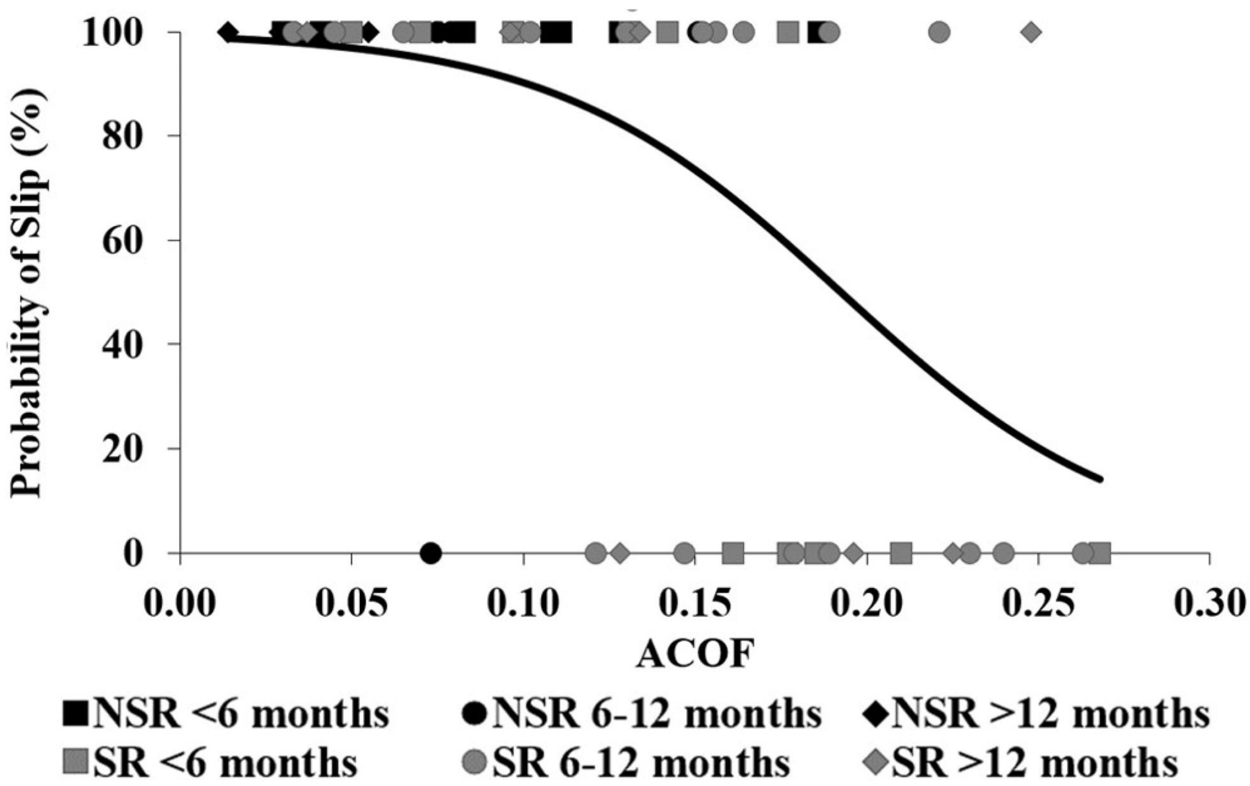

Figure 7.

Results from hypothesis 4: slipping was negatively correlated with the ACOF. Different markers represent different slip-resistant categories and shoe age.

Table 1.

The statistical analyses for all four hypotheses. Hypothesis H1A is for the multivariate analysis and H1B is the univariate analysis. “SRC” is the effect of the slip-resistant shoe category (SR and NSR).

Hypothesis	H1A	H1B	H2	H3	H4
Independent Var.	Worn Region	Worn Region	Worn Region	Fluid Pressure	ACOF
Dependent Var.	Slip Outcome	Slip Outcome	Fluid Pressure	ACOF	Slip Outcome
Covariates	SRC RCOF	-	SRC SRC*Worn Region	SRC SRC*Fluid pressure	RCOF