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Traction performance across the life of slip-resistant footwear: Preliminary results from a longitudinal study

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ABSTRACT

Introduction: Slips, trips, and falls are a major cause of injury in the workplace. Footwear is an important factor in preventing slips. Furthermore, traction performance (friction and under-shoe fluid drainage) are believed to change throughout the life of footwear. However, a paucity of data is available for how traction performance changes for naturally worn, slip-resistant footwear. *Method:* The presented research is a preliminary analysis from an ongoing, larger study. Participants wore slip-resistant footwear while their distance walked was monitored. Friction and under-shoe fluid pressures were measured using a robotic slip tester under a diluted glycerol contaminant condition after each month of wear for the left and right shoes. The size of the worn region was also measured. *Results:* Friction initially increased and then steadily decreased as the distance walked and the size of the worn region increased. Fluid pressures increased as the shoes were worn and were associated with increased walking distance and size of the worn region. *Discussion:* Consistent with previous research, increases in the size of the worn region are associated with increased under-shoe fluid pressures and decreased traction. These trends are presumably due to reduced fluid drainage between the shoe-floor interface when the shoe becomes worn. *Conclusions:* Traction performance changes with natural wear. The distance walked in the shoe and the size of the worn region may be valuable indicators for assessing loss of traction performance. *Practical Applications:* Current shoe replacement recommendations for slip-resistant shoes are based upon age and tread depth. This study suggests that tools measuring the size of the worn region and/or distance traveled in the shoes are appropriate alternatives for tracking traction performance loss due to shoe wear.

1. Problem

Slips, trips, and falls are a major concern in the workplace. In 2017, they accounted for 26% of nonfatal occupation injuries in the United States (U.S. Department of Labor - Bureau of Labor Statistics, 2019). According to a 2017 report, over $18 billion was devoted to workers' compensation from falls (Liberty Mutual Research Institute for Safety, 2017). Over 40% of all fall-related injuries have been shown to result from slipping (Courtney, Sorock, Manning, Collins, & Holbein-Jenny, 2001).

A slipping event occurs when there is insufficient traction between the shoe and the floor, often in the presence of a liquid contaminant (Burnfield & Powers, 2006; Hanson, Redfern, & Mazumdar, 1999). The measure typically describing this traction between two surfaces that resists slipping is the available coefficient of friction (ACOF). The ACOF of footwear can be measured using a variety of mechanical slip-testing devices that slide a shoe across a contaminated surface approximating a slipping event (Aschan, Hirvonen, Mannelin, & Rajamäki, 2005; Beschorner, Redfern, Porter, & Debski, 2007; Chang et al., 2001; Grönqvist, 1995; Hemler, Charbonneau, et al., 2019; Singh & Beschorner, 2014).

Footwear is a modifiable factor for reducing slips in the workplace. Shoes marketed as slip-resistant (SR) have been shown to have greater ACOF (Beschorner, Jones, & Iraqi, 2017) and a reduced rate of slipping compared to non-SR shoes (Verma et al., 2011). The outsoles of SR shoes tend to have patterns of small tread that are separated by channels. The channels provide paths for fluid drainage in the presence of a liquid contaminant (Hemler, Charbonneau, et al., 2019; Strandberg, 1985; Tisserand, 1985). The absence of tread channels can cause the fluid between a shoe and flooring to become pressurized. High fluid pressures indicate that the shoe-floor contaminant system is operating in the mixed

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lubrication regime, resulting in a lower ACOF (Beschorner et al., 2017; Beschorner, Lovell, Higgs III, & Redfern, 2009; Moore, Menezes, Lovell, & Beschorner, 2012; Singh & Beschorner, 2014). This phenomenon has been verified during human participant testing; specifically, wearing SR shoes was associated with lower under-shoe fluid pressures and lower slip severity compared to non-SR shoes (Sundaram, Hemler, Chanda, Haight, Redfern, Beschorner, 2020). While footwear is clearly an important factor influencing slip risk, an incomplete understanding exists for how traction performance changes as the shoes become worn.

There is currently a paucity of research quantifying changes in the traction performance of shoes as the outsole becomes worn and tread patterns are reduced. Previous research has shown that newer shoes were associated with a reduction in workplace slip risk compared to older shoes (Verma et al., 2014). Furthermore, switching to a new pair of shoes in the workplace reduced slipping rate by 55% (Verma et al., 2014). However, this previous study assessed wear using just two time categories (<6 months and >6 months). Current shoe manufacturers provide shoe tread depth gauges for determining significant wear (ShoesForCrews, 2019). However, there could be confusion regarding the location for application of tread depth gauges since tread wears unevenly (Hemler, Charbonneau, et al., 2019). A longitudinal shoe wear study that tracked shoes based on reported months of wear found slight increases in ACOF with initial wear followed by decreases in ACOF with subsequent wear (Grönqvist, 1995). Traction performance of shoes progressively worn using an accelerated wear protocol of abrasive mechanical sliding has shown increased fluid pressures and decreased ACOF as shoes become worn (Hemler, Charbonneau, et al., 2019). High fluid pressures were identified as mechanisms contributing to reduced ACOF (Hemler, Charbonneau, et al., 2020). However, the effects of natural wear on ACOF is not well understood.

Recent research has determined that the size of the worn region is associated with under-shoe hydrodynamics, which may explain the loss of traction as shoes wear. Analysis of shoes worn down using abrasive mechanical sliding showed that the under-shoe fluid pressures increased as the size of the worn region grew (Hemler, Charbonneau, et al., 2019). This concept is consistent with hydrodynamics models (e.g., rectangular tapered wedge bearing) that predict an increase in film thickness of the fluid separating two surfaces (Fuller, 1956) and increased fluid pressures with a larger worn region. Preliminary research has shown that the size of the worn region may be a useful factor in predicting this film thickness between a shoe and floor, relevant to a slipping event (Hemler & Beschorner, 2019). This study aims to further this research by analyzing the effects of the size of the worn region on traction and fluid drainage for naturally worn shoes.

The purpose of this study was to quantify the effects of usage (distance walked) and wear (size of the worn region) on changes in traction performance (ACOF and under-shoe fluid drainage). A preliminary data set from a longitudinal study is presented.

2. Method

In the longitudinal study, each participant received slip-resistant shoes that were worn in the workplace every other month to allow for traction performance and size of the worn region data collection on the months when the shoes were not worn. The distance the shoes were worn was tracked using a pedometer. At baseline and after each month of wear, ACOF and under-shoe fluid drainage measurements were collected. To record the geometry of the tread, negative molds of the heel tread were created. This paper presents initial findings for data collected so far from this study.

2.1. Subjects & shoes

Seven participants (1 female participant – age: 26 years; height: 175 cm; mass: 76.8 kg; shoe size: 7.5 US Men's Sizing – and 6 males – mean age: 45.8 ± 12.3 years; mean height: 185.3 ± 10.0 cm; mean mass: 100.9 ± 8.3 kg; mean shoe size: 12.4 ± 1.7 US Men's Sizing) wearing one of the shoe brands from a larger study were included. The other requirement for inclusion was a cumulative walking distance of more than 200 km. The included participants were employed in diverse settings including transportation, utilities, education, health services, and the hospitality industry sectors. Inclusion criteria included: regularly wearing treaded shoes in the workplace; working on their feet for at least four hours in a typical day; having a BMI less than 35; and having no history of musculoskeletal injury in the previous 2 years. The study was approved by the University of Pittsburgh Institutional Review Board and the participants provided informed consent prior to participation in the study.

Participants were provided with either boots (safeTstep ®, Dawson 160004) or shoes (safeTstep ®, Blast Bouffee 159961) depending on their occupational requirements. Both the boots and shoes had the same tread design (Fig. 1). The outsole material was rubber with a Shore A Hardness of 65 for the shoe and 74 for the boot. Each shoe was outfitted with a pedometer (MilestonePod, Milestone Sports, Columbia, MD), (Hunter, Miller, & Suydam, 2017) to track the distance traveled in each shoe. Shoes were retired from the study when the under-shoe fluid force for either the left or right shoe was greater than 50 N (see Section 2.4), or when the outsole or upper (i.e., part of the shoe or boot above the sole) became too worn at the discretion of the participant.

2.2. Mechanical testing of shoes

A robotic slip tester (Fig. 2) was used to assess the traction performance of the shoes (see Hemler, Charbonneau, et al., 2019 for details). The device consisted of a force plate measuring shear and normal forces (BP400600-1K-Q2046, AMTI, Watertown, MA, 02472), an adjustable platform instrumented with fluid pressure sensors (Gems® 3100R10PG08F002) aligned in the X-direction, and three electromagnetic motors. One motor controlled the vertical displacement (Z-direction), and the two horizontal motors controlled the horizontal displacement (Y-direction) and the foot angle (YZ plane). Four fluid pressure sensors were aligned in the X-direction, embedded beneath the floor, spaced 25 mm apart

Fig. 1. Shoe tread pattern at the heel for all shoes in this study.

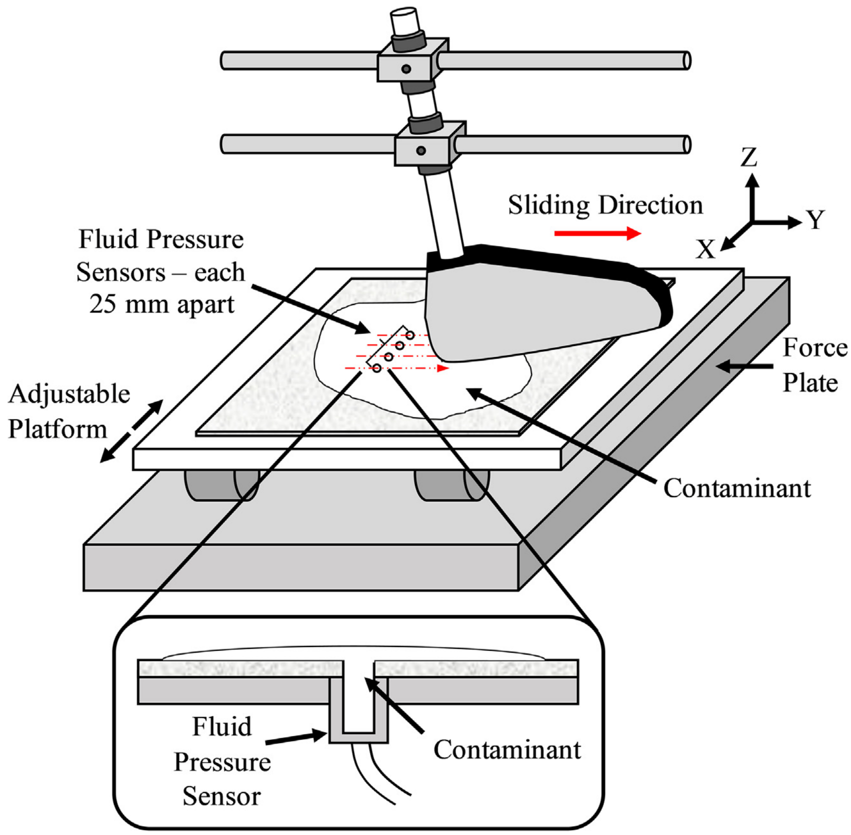

Fig. 2. The robotic slip tester was used to slide the shoe across the contaminated surface along multiple parallel paths (adapted from Hemler, Charbonneau, et al., 2019).

and had an inlet diameter of 3.2 mm. The device is similar to the Portable Slip Simulator device (Aschan et al., 2005; Iraqi, Cham, Redfern, & Beschorner, 2018; Jones, Iraqi, & Beschorner, 2018). Additionally this device has the ability to independently control the foot angle and has been used in previous research for traction performance testing (Hemler, Charbonneau, et al., 2019).

Using the robotic slip tester, the right and left shoes of each pair were tested using a contaminated surface at baseline and after each month of wear. A vinyl composite tile flooring (Armstrong, 51804; with surface roughness characteristics: $Ra = 2.19 \pm 0.29\ \mu m$, $Rz = 16.13 \pm 2.74\ \mu m$, $Rq = 3.13 \pm 0.42\ \mu m$; where Ra is the average asperity deviation from the mean line, Rz is the maximum asperity peak to valley distance, and Rq is the root mean square height of the profile) and a diluted glycerol contaminant solution (90% glycerol, 10% water by volume; 219 cP) were used. A sufficient amount of fluid was applied to the flooring to fully cover the floor asperities across the region that the shoe contacted. The contaminant was spread to cover the entire slipping area prior to each trial. To approximate the same conditions as a slipping incident, each shoe was slid at an angle of $17 \pm 1°$ (Albert, Moyer, & Beschorner, 2017; Iraqi et al., 2018), speed of 0.3 m/s (Albert et al., 2017; ASTM, 2011; Iraqi et al., 2018), and average normal force of $250\ N \pm 10\ N$ (Iraqi & Beschorner, 2017; Iraqi, Cham, Redfern, Vidic, & Beschorner, 2018). The platform was moved 5 mm in the positive X-direction between each trial for a total of 5 trials and 20 fluid pressure scans.

2.3. Worn region measurement

A mold of the heel tread was made at baseline and after each month of wear. The left and right heels were placed in a rectangular containment (92 mm × 76 mm × 28 mm) of silicone rubber compound (Smooth-On Inc.; Macungie, PA; Oomoo® 25) at an angle of 17° (Fig. 3). The largest region of continuous wear was identified in each mold and the length along the long axis of the shoe and the width along the short axis of the shoe were measured. For baseline values and when no worn region had yet formed, the length and width of one tread block was recorded. The product of these two measurements comprised the size of the worn region on each shoe.

2.4. Data analysis

The ACOF was determined as the peak of the ratio of the resultant shear forces to the normal force, averaged across a 200 ms time period. This time period started when the normal force first reached 250 N. Fluid pressures that exceeded 10 kPa were included in the analysis. A numerical integration technique was used to determine the load supported by the fluid (hereafter, referred to as the fluid force) for each shoe (Beschorner, Albert, Chambers, & Redfern, 2014; Hemler, Charbonneau, et al., 2019). If either the right or left shoe reached a fluid force greater than 50 N, the pair of shoes was retired from the study as it was deemed unsafe for continued use (Hemler, Charbonneau, et al., 2019).

The aims of this study were to quantify traction performance in response to increased usage and growth of the size of the worn region. Thus, the ACOF and fluid force were the dependent variables. Predictor variables included the distance walked and size of the worn region. The analyses controlled for shoe side (left vs. right).

Repeated-measures ANOVA methods were used to analyze the effects of the predictor variables (size of worn region, distance

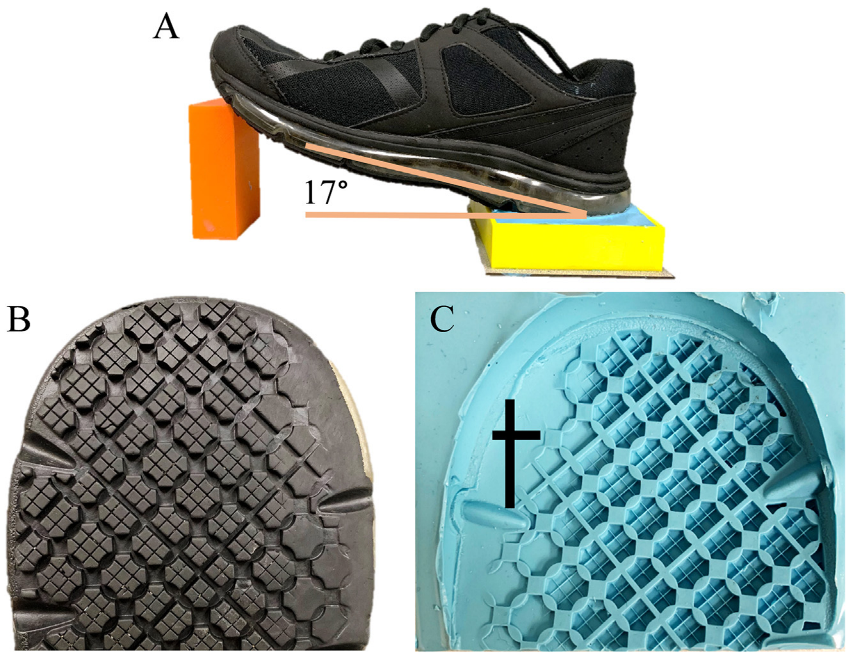

Fig. 3. (A) Molds of shoe heels were created at a 17° angle to capture the (B) shoe tread geometry. C) The mold was used to measure the length and the width of the largest continuous area without tread at baseline and after each month of wear.

walked) on the dependent variables (ACOF, fluid force). Specifically, two models were used to determine the response of ACOF and fluid force to the distance walked in the shoes (continuous). Two additional models were used to determine the response of ACOF and fluid force to the size of the worn region (continuous). Separate analyses were used for distance walked and the size of the worn region as predictor variables since these variables are correlated (Supplementary Materials). Participant was a random variable in these models. To normalize the residuals, a square transformation was applied to the ACOF data and a cube root transformation was applied to fluid force data prior to statistical analyses. To correct for a positive skew, a square root transformation was applied to the distance walked.

3. Results

A total of 35 subject-months of data are reported ranging from 3 to 10 months per participant. The total distance walked ranged from 220 to 1255 km with an average ± standard deviation total distance of 231 ± 262 km and a monthly average of 76 ± 82 km. One pair of shoes was retired from the study due to the left shoe exceeding the 50 N fluid force safety threshold. Four pairs of shoes were retired due to significant wear to the footwear upper. Two participants are still enrolled in the study (S6 & S7). For all shoes, the worn region in a single region (13 cases on the lateral side and 1 case on the medial side) and a single wear patch grew with subsequent use.

The ACOF ranged from 0.081 to 0.212 (Fig. 4) throughout the study and ACOF ranged from 0.134 to 0.207 at baseline. An increase in walking distance was associated with a decrease in ACOF ($F_{1,84}$ = 65.9, p < .001). There was an initial increase in ACOF for four left shoes and five right shoes (9 out of 14 shoes). Of these shoes, the ACOF fell below the baseline ACOF after 128 ± 64 km of wear. After 210 km of wear, ACOF decreased from the baseline level for all shoes. The average ACOF decrease was 0.053 ± 0.032 (28.1 ± 13.6%) from baseline to present data collection. Across participants, the average (standard deviation) ACOF at baseline, from 0 to 200 km, and at each participant's last datum were 0.18 (0.023), 0.17 (0.030), and 0.13 (0.022), respectively.

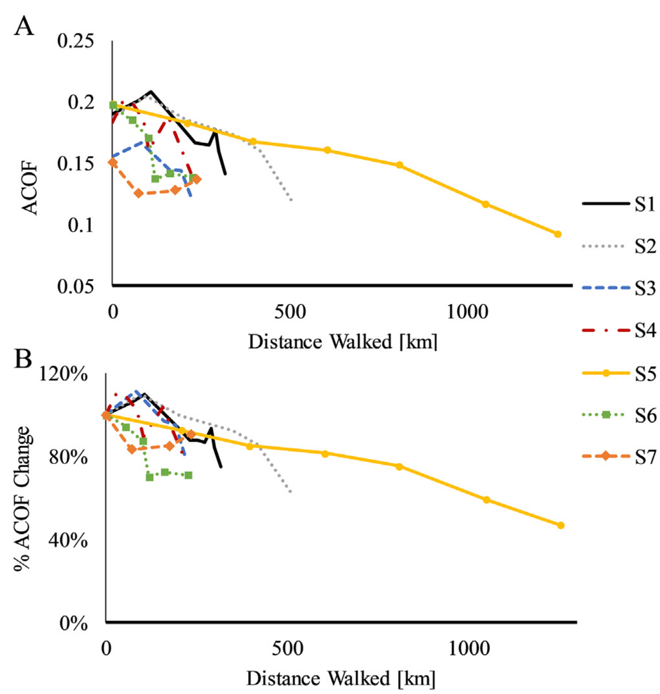

Fig. 4. (A) ACOF plotted against the distance walked for each participant. (B) ACOF across the distance walked in the shoes as a percentage of the baseline ACOF. ACOF and percent of baseline ACOF are averaged across left and right shoe sides.

An increase in the distance walked was associated with increased fluid force ($F_{1,86}$ = 44.2, p < .001). The fluid force ranged from < 0.1 to 63.8 N (Fig. 5). Using the regression equation ($\text{fluidforce[N]} = (1.16 + 0.05\sqrt{\text{DistanceWalked[km]}})^3$), walking distances of 200 km and 1000 km were associated with an increase in fluid force of 6 N and 19 N, respectively.

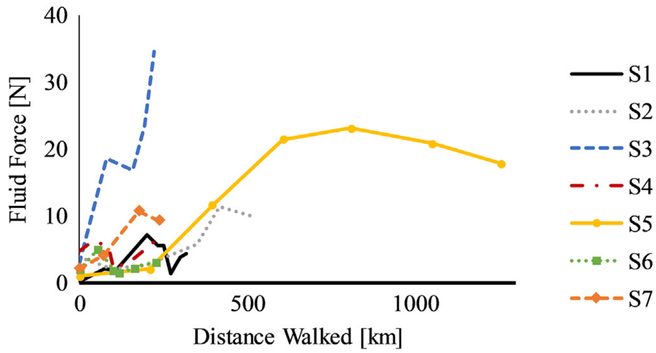

Fig. 5. Fluid force values are plotted against the distance walked which was averaged across the left and right shoes per subject.

The size of the worn region ranged from 12 to 2432 mm^2 and increased with respect to the distance walked (additional details available in Supplemental Materials) (Fig. 6). ACOF decreased as the size of the worn region increased ($F_{1,85} = 36.0$, $p < .001$). When the size of the worn region grew to 1000 mm^2 and 2000 mm^2, the ACOF was predicted to decrease from baseline by 0.03 and 0.08, respectively ($\mathrm{ACOF} = \sqrt{0.03 - 0.000011 * \mathrm{SWR[mm^2]}}$). The increase in fluid force was associated with increases in the size of the worn region ($F_{1,76} = 59.2$, $p < .001$). Using the regression equation, $\mathrm{fluidforce[N]} = (1.3 + 0.00086 * \mathrm{SWR[mm^2]})^3$, the fluid force was predicted as 11 N after the size of the worn region grew to 1000 mm^2 and as 29 N after the size of the worn region reached 2000 mm^2.

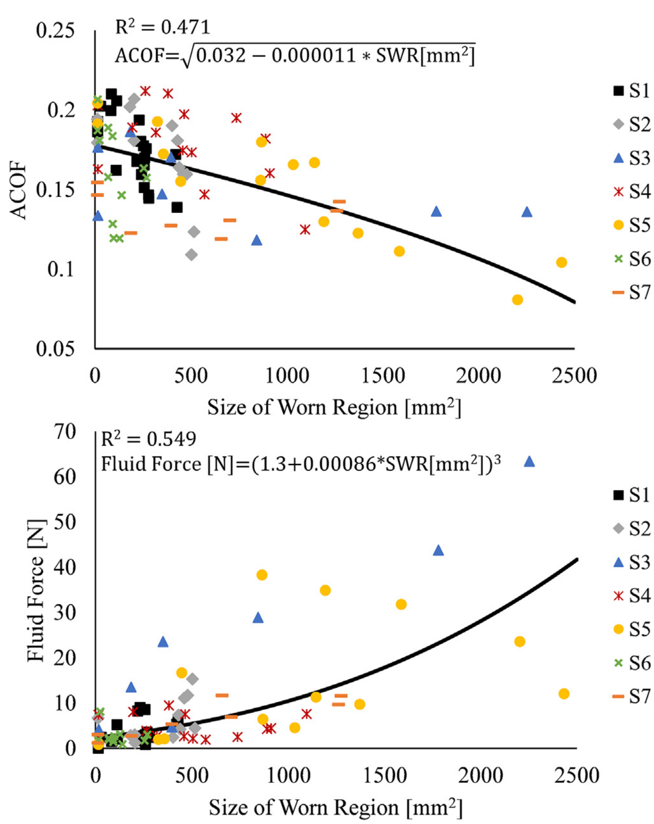

Fig. 6. (A) ACOF plotted against the size of the worn region. Different markers are used for each participant (legend). (B) Fluid force plotted against the size of the worn region for all participants. Left and right shoe averages are shown for each participant. The regression functions for each model are shown with the solid black line (SWR ≡ size of worn region [mm^2]). The regression equations and the R^2 values are shown in the top left of each plot.

4. Discussion

In this study, ACOF decreased and the fluid force generally increased as SR shoes became more worn. The increase in fluid pressure partially explains the decreased traction. There was an initial increase in ACOF from baseline for 9 of the 14 shoes, though the ACOF then decreased from baseline for all of the shoes after at most, 210 km of usage. The fluid force increase was associated with the increasing size of the worn region, presumably due to reduced fluid drainage.

The effects of usage and wear on ACOF and fluid force from this analysis are consistent with previous research. For progressively worn shoes using natural and simulated wear respectively, Grönqvist (1995) and Hemler et al. (2019) reported an initial increase in ACOF followed by a decrease across the life of the shoes. In this study, similar trends are seen for the majority of the naturally worn shoes with an initial increase in ACOF for distances less than 210 km and subsequent decrease in ACOF. The increase in fluid force with increased wear is also consistent with previous studies (Hemler, Charbonneau, et al., 2019). The relationship between fluid force and size of the worn region is consistent with previous research that utilized an accelerated wear protocol to generate shoe wear (Hemler, Charbonneau, et al., 2019). Fluid force increased as the size of the worn region increased similar to Hemler, Charbonneau, et al. (2019), and consistent with hydrodynamic theory (Hamrock, Schmid, & Jacobson, 2004). Therefore, this study adds to a growing body of evidence that traction performance degrades over usage and that this degradation can be assessed based on the size of the worn region.

The variation of ACOF observed in this study was within a critical range for determining slip likelihood. Human slipping studies have shown that the probability of a slip on level ground changes dramatically within the range of 0.12–0.21 (Burnfield & Powers, 2006; Hanson et al., 1999; Iraqi et al., 2018). Both the baseline ACOF values and the changes in ACOF due to wear vary within this range. This variability is not believed to be due to the device since repeatability is less than 0.01 for the portable slip tester (Beschorner, Iraqi, Redfern, Moyer, & Cham, 2019), which is functionally similar to the slip testing device used in this study. The variation in ACOF at baseline for the shoes, reference Fig. 4A may be due to different heel tread block placements that arise from variations in shoe size-dependent molds. For example, on the heel, the general tread pattern is the same for all shoes. However, on the edges, some individual tread blocks are cut differently to fit the heel of the appropriate shoe size. These variations in tread on the edges may affect the ACOF.

This preliminary study has certain limitations. A single shoe tread pattern was used in order to limit variability across the participants. However, this limited the generalizability of the results to other types of shoes. The shoes were tested on the slip-testing device with a 0° medio-lateral tilt. Wear generally appeared first on the lateral side of the shoe outsoles, which may indicate that participants walked with a slight medio-lateral inversion. The slip testing device was unable to accommodate individual inversion angles, which may have led to the tread contact region being incongruent between traction performance testing and actual walking.

5. Summary

The results found an association between the size of the worn tread region and traction performance loss for naturally worn, slip-resistant shoes. Consistent with accelerated wear experiments, an initial increase in friction was observed at low distances of usage followed by a steady decrease in friction with increasing distance. Fluid force measurements suggest that this steady decrease in traction is caused by an increase in hydrodynamic effects. The increase in hydrodynamic effects coincide with an increase in the size of the worn region, consistent with hydrodynamic theory. This study supports that usage and wear measures presented in this study are beneficial tools in mapping traction performance for slip-resistant shoes.

6. Practical Applications

The distance for which shoes have been worn and the size of the worn region may be useful tools for monitoring traction performance changes. Specifically, these metrics correlate with ACOF and fluid force and are realistic for determining shoe replacement thresholds for natural wear. For example, observing the size of the worn region is achievable via self-monitoring and the distance walked is practical to monitor given increased use of wearable sensors for worker safety monitoring. Thus, these metrics may provide an opportunity for employers and employees to monitor shoe wear condition to inform replacement.

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Appendix A. Supplementary data

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