

## A. COVER PAGE

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<b>hESC:</b> No	<b>Inventions/Patents:</b> No

## B. ACCOMPLISHMENTS

### B.1 WHAT ARE THE MAJOR GOALS OF THE PROJECT?

#### Specific Aims:

Slip-resistant shoes have emerged as an effective counter-measure in reducing workplace slip and fall accidents [3]. The slip-resistance of shoes is typically characterized by the coefficient of friction (COF) between the shoe and floor surface in the presence of a fluid contaminant. Our preliminary experimental and modeling research has determined that shoe tread design features have a major impact on shoe-floor COF and that the COF varies substantially across different shoes that are labeled as slip-resistant. While testing standards exist for evaluating the slip-resistance of shoes, slip-testing data is rarely available to workers or companies and the cost to conduct testing can be cost-prohibitive. Thus, alternative means of assessing the slip-resistance of footwear may be needed to inform better slip-resistant footwear selection. An alternative strategy to traditional COF testing is to develop prediction equations for shoe-floor-contaminant COF based on measurable tread features. The feasibility of this approach is supported by preliminary experimental and modeling work conducted by the investigators. A model that predicts shoe-floor-contaminant COF based on shoe tread features would enhance: 1) appropriate selection of slip-resistant shoes; and 2) slip-resistant shoe design. Previous research has identified shoe sole features that influence COF and can be inexpensively measured: hardness, contact area and orientation of tread edges. The overall goal of this R03 application is to develop a predictive model for shoe-floor-contaminant COF based on measurable parameters of the shoe, floor and fluid contaminant. The central hypothesis of this proposal is that shoe-floor-contaminant COF and slip-risk can be predicted based on the characteristics of the shoes. This proposal includes the following innovative concepts: 1: the shoe will be characterized using parameters that are both easy to measure and have been shown to contribute to the tribological mechanisms relevant to slipping; and 2: cross-validation techniques will be implemented to identify the best prediction model. The proposed research consists of two aims:

**Specific Aim 1:** Develop and validate a regression model for predicting the slip-resistance of shoes based on the characteristics of the shoe outsole. A regression model utilizing tread features (tread hardness, contact area and the orientation of tread edges), floor roughness and fluid viscosity will be constructed from experimental data obtained using a whole-shoe slip-tester. Twenty-one slip-resistant shoes and twenty-nine non-slip-resistant shoes will be tested against three common floor surfaces with three common fluid contaminants. The regression model will be built using ANOVA methods and the best-predictive model will be identified using k-fold cross-validation methods.

**Hypothesis 1.1:** The model will predict the COF values of shoe-floor-contaminant friction

**Hypothesis 1.2:** Soft shoes, higher contact area and tread oriented perpendicular to the slipping direction will be correlated with hysteresis friction.

**Hypothesis 1.3:** Soft shoes and higher contact area will be correlated with adhesion friction.

**Specific Aim 2:** Validate the findings of Aim 1 using unexpected human slips. Thirty human subjects will be unexpectedly slipped, while being randomly assigned to wear shoes of varying design. The predicted COF of the shoes will be used to predict slip outcomes. The validity of the model to predict the outcomes, the sensitivity and specificity will be quantified.

**Hypothesis 2:** The COF predicted by the model (from Aim 1) will predict the risk of slip incidence.

The results of this study are expected to establish a basis for designing and selecting slip-resistant shoes. Successful completion of the grant will lead to an R01 application that will: 1) generalize this model to a greater number of flooring and fluid contaminants; and 2) prospectively assess the model developed in this grant by tracking its ability to predict slips in the workplace. This proposal meets several NORA objectives including Manufacturing Goal 2, Wholesale and Retail Trade Goal 2 and several goals for the Service sector. The proposed research aims to make shoe-floor tribology research more accessible to ergonomics and safety professionals and therefore exemplifies research to practice (R2P) concepts.

**B.1.a Have the major goals changed since the initial competing award or previous report?**

No

**B.2 WHAT WAS ACCOMPLISHED UNDER THESE GOALS?**

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**B.3 COMPETITIVE REVISIONS/ADMINISTRATIVE SUPPLEMENTS**

**For this reporting period, is there one or more Revision/Supplement associated with this award for which reporting is required?**

No

**B.4 WHAT OPPORTUNITIES FOR TRAINING AND PROFESSIONAL DEVELOPMENT HAS THE PROJECT PROVIDED?**

NOTHING TO REPORT

**B.5 HOW HAVE THE RESULTS BEEN DISSEMINATED TO COMMUNITIES OF INTEREST?**

NOTHING TO REPORT

**B.6 WHAT DO YOU PLAN TO DO DURING THE NEXT REPORTING PERIOD TO ACCOMPLISH THE GOALS?**

Not Applicable

# FINAL PROGRESS REPORT

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## B. List of Terms and Abbreviations

ACOF: Available coefficient of friction (synonymous with coefficient of friction)

$\beta$ : Regression coefficient

$\beta_{COF_{Predicted}}$ : Regression coefficient associated with  $COF_{Predicted}$

$\beta_{Flooring}$ : Regression coefficient for flooring

$\beta_{Hardness}$ : Regression coefficient for hardness

$\beta_{Heel\ Shape}$ : Regression coefficient for heel shape

$\beta_{RCOF}$ : Regression coefficient of RCOF

$\beta_{Shoe\ Type}$ : Regression coefficient for shoe type

$\beta_{Shoe\ Type,Hardness}$ : Regression coefficient for the interaction between shoe type and hardness

$\beta_{Shoe\ Type,Heel\ Shape}$ : Regression coefficient for the interaction between shoe type and heel shape

$\beta_{Shoe\ Type,Tread\ Surface\ Area}$ : Regression coefficient for the interaction between shoe type and tread surface area

$\beta_{Tread\ Surface\ Area}$ : Regression coefficient for tread surface area

$\beta_0$ : Regression coefficient – intercept

AUC: Area under the receiver operating characteristic curve.

COF: Coefficient of friction (synonymous with available coefficient of friction)

$COF_{Predicted}$ : The predicted COF value from the regression model presented Eq. (11)

$F_{Transverse\ Shear}$ : Shear force in the direction transverse to the sliding direction for the frame

$F_{Longitudinal\ Shear}$ : Shear force in the sliding direction for the frame

$F_{Normal}$ : Normal force for the frame

NSR: Shoes that are not labeled as slip-resistant

$R_a$ : Average roughness of a surface profile

RCOF: Required coefficient of friction

$R_{dq}$ : Root-mean square of a surface slope

$R_q$ : Root-mean-square deviation of a surface profile

$R_z$ : Mean peak to valley height of surface profile

Shore A: Shore A hardness value

SR: Shoes labeled as slip-resistant

S: shape factor of the tread blocks based on the loaded area and surface area free to bulge

### C. Abstract

Title: A Predictive Statistical Model for Shoe-Floor-Fluid Coefficient of Friction

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Slip and fall accidents are a major and growing source of occupational injuries. Slip-resistant shoes with a high coefficient of friction (COF) are effective at a reducing slipping risk. However, neither experts nor industry has agreed upon a consistent set of criteria for labeling a shoe as slip-resistant. A consequence of this lack of standardization is that significant variability exists across shoes that are labeled slip-resistant. Furthermore, independent testing of shoe COF is expensive, which may limit its use by employers and employees. The proposed research aims to address this problem by developing a predictive model for shoe-floor-contaminant COF based on shoe parameters that can be measured with little cost. The overall objective of this R03 study is to train and validate a statistical model for predicting the COF of footwear against a floor surface in the presence of a liquid contaminant.

**Aim 1:** Using mechanical friction experiments, we characterized the friction response of 73 shoes including 58 slip-resistant shoe designs and 15 non-slip-resistant shoe designs. A prediction model was developed that predicted 88% of the variability in friction performance across slip-resistant shoes based on the tread surface area, shoe beveling, and hardness, while controlling for the flooring. This model did not apply to non-slip-resistant shoes due to the presence of fluid pressures. Thus, strategies to improve the friction performance of slip-resistant shoes may consider the design parameters utilized in this study, while strategies to improve friction performance of non-slip-resistant shoes should prioritize improving fluid drainage. Safety managers intending to use this model should be aware that it only applies to slip-resistant shoes.

**Aim 2:** The model was validated based on 38 human slips in oily conditions. The model was found to sensitively predict whether a participant would experience a slip. Thus, the model appeared to provide friction predictions that are relevant to human safety.

This study led to numerous outputs and outcomes. The work was disseminated by 1 published peer-reviewed paper (1 more in review and 2 in preparation) and several presentations that targeted the scientific, footwear producer, and safety professional communities.

## D. Section 1 of the Final Progress Report

### D.1. Significant or Key Findings.

This study led to the development and validation of a statistical model to predict friction performance and slipping consistent with the two aims that were proposed.

#### D.1.1. Aim 1: Develop and validate a regression model for predicting the slip-resistance of shoes based on the characteristics of the shoe outsole.

##### D.1.1.1. Major Activities:

We tested fifty-eight slip-resistant (SR) and fifteen non-slip-resistant (NSR) outsoles in oily conditions on two floor surfaces to develop a prediction model for friction based on outsole features. Coefficient of friction (COF) data was collected using the portable slip simulator utilizing test conditions that resemble and predict human slips (e.g., shoe-floor angle of 17°, normal force 250 N). Hysteresis friction was measured in the presence of canola oil to minimize adhesion and represent a worst-case contaminant condition. Footwear outsole features such as material hardness, tread surface area, heel width and heel shape were selected for measurements based on their association with hysteresis friction from previous research. Additionally, shoe outsole metrics were selected to be low-cost to make the assessment accessible to practitioners. Multiple step-wise regression models (forward selection, backward elimination, and hybrid) were performed to ensure that the resulting models were not an artifact of the stepwise approach. K-fold cross-validation methods were used to capture the error in the models without overfitting the data. These models were conducted on the SR shoes first and then on the combined set including both SR and NSR shoes. For the SR shoes, under-shoe fluid pressures were also measured to assess fluid drainage. Lastly, an analysis was conducted to determine if the model could extend to non-oily conditions where diluted sodium laurel sulfate (SLS, similar to a detergent solution) was utilized.

##### D.1.2. Results: Slip-Resistant (SR) Shoes in Oily Conditions

Results indicated that 87% of ACOF variation was explained by three shoe outsole parameters (tread surface area, heel shape, hardness) and floor type (**Fig. 6**) (Section E.2.1.). An increase in the tread surface area from the first quartile (9.6) to the third quartile (13.4) increased ACOF by 0.057. The change from flat-edge to beveled edge heel shape increased ACOF by 0.041. An increase in the Shore A hardness from the first quartile (49.8) to the third quartile (60.8) reduced ACOF by 0.033. The results regarding the shoe hardness and contact area supported the *a priori* hypotheses detailed in the grant application. Tread orientation (part of Hypothesis 1.2) was not evaluated because we determined that commercially-developed tread could not be easily characterized with this parameter. Instead, other parameters including shoe beveling, and shape factor were included in the model.

##### D.1.3. Results: Non-Slip-Resistant Shoes (NSR) in Oily Conditions

The tread features that predicted friction performance for SR shoes did not apply to NSR shoes (Section E.2.2.). The model developed from slip-resistant shoes in oily conditions consistently overestimated friction performance in the NSR shoes. When a new model was developed, interaction effects were observed between SR category and the tread parameters suggesting that these parameters were less predictive for NSR shoes. The reason for this finding may be related to the drainage capacity of NSR shoes. High fluid pressures were observed for several of these shoes and the fluid pressure was the main variable predicting performance for NSR shoes. Therefore, strategies focused on enhancing drainage capacity may be more appropriate for NSR shoes than strategies such as enhancing tread surface area.

##### D.1.4. Results: SR shoes in non-oily conditions

Shoe friction performance in oily conditions were only weakly correlated with friction in SLS solution (Section E.2.3). Complex and difficult to interpret interaction effects were observed when including SLS conditions to the regression model suggesting greater complexity in making

these predictions. Furthermore, RMS error was higher for SLS than oily conditions. However, nearly all of the shoes had a higher friction performance in SLS than oily conditions suggesting that shoes that were safe for oil would also be safe in the presence of SLS.

## **D.2. Aim 2: Validate the findings of Aim 1 using unexpected human slips.**

### **D.2.1. Major Activities:**

We collected data on human participants to determine whether the COF prediction model developed for SR shoes in oily conditions could predict slipping risk. Human gait data were collected from 38 participants who each donned different SR shoe designs and were exposed to an oily floor surface. The coefficient of friction was predicted for these SR shoe designs based on tread surface area, hardness, and the heel shape. Logistic regression analyses were performed to determine if the predicted COF was associated with slipping risk.

### **D.2.2. Predicting slips based on tread features**

The predicted coefficient of friction was significantly associated with a reduction in slipping risk consistent with *a priori* expectations (Section E.2.4.). This finding was consistent with the univariate model and a multivariate model (with individual required coefficient of friction entered as a covariate). The slipping odds ratio was 0.291 for shoes with predicted friction performance in the third quartile relative to shoes in the first quartile. This study suggests that the model developed in Aim #1 for SR shoes on oily surfaces was valid for assessing human slipping risk.

## **D.3. Translation of findings:**

Translation and dissemination efforts have focused on three pathways: 1) disseminating scientific knowledge to the research community (Section F), 2) disseminating knowledge on footwear design to footwear designers, and 3) disseminating footwear inspection information to workers and safety professionals.

**1: Scientific knowledge to research community:** This research has been presented to the scientific community through 1 peer-reviewed manuscript (also 1 in review and 3 in preparation), one PhD dissertations, 3 conference presentations, and 4 invited talks. One talk included a Keynote lecture at the International Slips, Trips, and Falls meeting (Madrid, February, 2020).

**2. Dissemination to footwear designers and safety professionals:** Research has been communicated to footwear companies involved in designing, manufacturing, and selling footwear via eight presentations. This data was presented in eight presentations to this audience. Furthermore, we presented this research during eight presentations where safety professionals that were involved in footwear decision making processes were in the audience.

## **D.4. Research Outcomes/Impact.**

### **D.4.1. Potential outcomes**

We expect that this research will inform the design choices of footwear companies to alter their shoe design to incorporate heel beveling and increase tread surface area where appropriate. Furthermore, we expect that the methods that were developed may be utilized by safety professionals to identify good and poor performing shoes. Thus, we expect that this research may inform better design and selection processes, which could have an effect of reducing slips.

### **D.4.2. Intermediate outcomes**

One producer of slip-resistant shoes (SR Max) has incorporated this research into their design process: "We are trying to increase the surface contact at the heel." "We also are working to ensure the bevel in the back is in line with your recommendations". Thus, this research has achieved intermediate outcomes through design of safer footwear.

### **D.4.3. End outcomes:**

None

## E.Section 2 of the Final Progress Report: Scientific Report.

### E.1. Background

#### E.1.1. Problem Statement and Significance

Slips and falls are among the leading and fastest growing sources of occupational accidents. In 2019, slip, trip and fall events accounted for approximately 24% of all non-fatal occupational accidents [1]. Approximately 40 % of all falls are initiated by a slipping event [1].

#### E.1.2. Previous studies on the contributions of shoe design to slip risk

Several factors impact slips and falls with friction having the greatest influence. Logistic regression models have consistently demonstrated that the risk of a slip is dependent on the amount of friction between the shoe and floor surface and the required friction for walking [2, 3]. The available friction at the shoe-floor interface is commonly measured using a slip-tester [4-6] although it also can be predicted with computational models as shown in the work of our recently completed NIOSH-funded project [7-10]. Other factors that influence the outcome of a slip include biomechanics of locomotion, the effectiveness of a recovery response, and personal factors such as age [11-15]. While these factors are important in evaluating slip risk, enhancing shoe-floor friction through footwear and flooring controls has been shown to be an effective strategy [16-18] and is consistent with traditional ergonomics approaches of fitting the workplace to the individual. The proposed research continues an existing line of investigation to reduce slip and fall accidents by understanding and influencing the critical factors that cause low friction.

The utilization of slip-resistant shoes has emerged as an effective strategy in preventing slipping accidents. Specifically, slip-resistant shoes have been found to reduce slipping by about 30-70% less than those wearing non-slip-resistant shoes [18-22]. The authors of these previous studies have noted that differences may exist across slip-resistant shoes and that no standard currently exists for identifying slip-resistant shoes. Therefore, the impact of high performing slip-resistant shoes may be underestimated by this research and the effect of low performing slip-resistant shoes may be overestimated in these studies.

The coefficient of friction (COF) between shoe and floor surfaces is predictive of the overall slip risk. Specifically, when the COF exceeds the amount of friction required for walking (termed the required coefficient of friction), the risk of a slip decreases ([3, 23]). Even modest increases in the available COF have been shown to dramatically reduce slip risk when the available and required friction are approximately equal. In fact, our research group determined that increasing shoe-floor-contaminant friction from 0.15 to 0.18 using softer shoe outsole materials reduced slipping risk from ~40% to 8% [24]. Thus, identifying shoe features that increase the shoe-floor COF has significant potential for reducing slipping risk.

The features of shoe tread have been repeatedly shown to affect the shoe-floor-contaminant COF. Several shoe features are known to influence slip-resistance including shoe hardness [25, 26], shoe roughness [25-28], tread width [29-31], tread depth [26, 31-33], tread orientation [30, 34], contact area [35, 36] and shoes that are labeled slip-resistant [37]. Specifically, softer shoe outsole materials have been shown to improve friction against Teflon floors [38] and contaminated flooring [10, 26, 39]. Shoes with higher outsole roughness provide better friction against ice [25] and contaminated flooring [8, 39]. Also, contact area of the shoe has been shown to prospectively predict the slip risk of older adults [36] and has been shown to correlate with coefficient of friction of oily floors [40]. At the time that we submitted this grant application, just six of the studies examining the impact of footwear on COF utilized real shoes (as opposed to custom-made shoe samples) against floor surfaces (as opposed to ice) [26, 32-34, 37, 38] and just one of those six studies considered more than three shoe outsoles [37]. Furthermore, the only study to have considered more than three shoes was a report posted by

the Health & Safety Laboratory (UK), which was not peer reviewed, lacks sufficient detail to be reproducible and does not correlate the shoe outsole features with COF [37]. Thus, additional research was needed to determine the tread features that consistently predict shoe COF across a wide range of shoe designs.

A tribological framework is critical to identifying the tread features that contribute most to shoe-floor contaminant friction. Our research group has identified four tribological mechanisms that are relevant to shoe-floor-contaminant friction: under-shoe hydrodynamic pressures, boundary lubrication, adhesion and hysteresis. Hydrodynamic pressures have been measured by our group with fluid pressure sensors that are recessed into the floor and are primarily caused by shoes that have become very worn [32, 33]. This mechanism is currently being assessed in a complementary NIOSH R01 grant that aims to develop shoe maintenance (replacement) recommendations. In the absence of hydrodynamic pressures, the dominant tribological mechanisms are hysteresis, adhesion and boundary lubrication [8, 10]. Hysteresis friction is caused by viscoelastic deformation of the shoe material by the floor asperities [8, 41, 42]. Our previous research has determined that hysteresis friction can be increased with rougher shoe and floor materials, reducing the average contact pressure and orienting shoe tread perpendicular to the sliding direction [8]. Adhesion is typically a function of the real contact area and the adhesional shear stress between the surfaces (a function of the shoe and floor material). Our previous research has determined that adhesion friction can be increased by reducing the shoe hardness, reducing the contact pressure and reducing shoe and floor roughness [8, 42]. Boundary lubrication reduces adhesion friction but not hysteresis friction by reducing the adhesion shear stress between the surfaces. Higher viscosity fluids and fluids with longer molecular chains are associated with reduced adhesion friction in boundary lubrication [9, 10]. *This proposed research focuses on the features that are known to contribute to hysteresis friction (contact area, hardness, tread orientation and floor roughness, Study #1) and adhesion friction (hardness, contact area, and fluid viscosity, Study #3) in boundary lubrication. We also explored the impact of shoe features on friction performance in cases where hydrodynamic lubrication effects were present (Study #2)*

Current methods for testing slip-resistance of footwear are expensive. The methods most commonly used for testing footwear require expensive robotic devices or inclinable ramps [4]. The cost for requesting independent shoe-floor-friction tests are approximately \$250 for a single shoe-floor-contaminant combination, which is prohibitively expensive in work places with variable flooring and fluid contaminants. This cost burden is a major obstacle to controls that specify appropriate footwear for a workplace. The proposed research aims to develop regression models that will allow for the prediction of shoe slip-resistance without the need for expensive testing. Furthermore, these models will be validated against human slipping outcomes to ensure their relevant to human ambulation (Study #4). Thus, this approach is expected to achieve broader adoption in industry.

## **E.2. Methodology, Results and Discussion**

### **E.2.1. Aim #1, Study #1: Prediction of coefficient of friction based on footwear outsole features**

#### **E.2.1.1. Methods**

This study consists of three main components: shoe outsole tread measurements, ACOF measurements, and statistical model building. Geometric and material measurements were made from the outsole tread of fifty-eight footwear designs. ACOF measurements were conducted using a robotic whole shoe tester for these shoes against two types of flooring. A multiple linear regression model was developed using stepwise regression methods including k-fold cross-validation.

**E.2.1.1.1. Materials:**

Sixty-three footwear that were marketed as slip-resistant from six brands (Shoes for Crews, Tredsafe, SR Max, SafeTstep, Dr. Scholl's, and Timberland PRO®) with low-collar height and laces were selected for this study (Table 1). No alternative footwear was included such as overshoes, slip-on, and clog shoe since wearing alternative footwear tends to lead to different slipping biomechanics [43] and may be inappropriate for the specified ACOF test methods. Slip-resistant footwear included casual, work, athletic and dress style that were marketed as men's, women's, and unisex shoes. Shoe selection was aimed to achieve variation in outsole geometry and material hardness between and within shoe brands. Twenty of the selected footwear (four per each brand, except Timberland PRO®) were modified to systematically control outsole geometry. Three pairs of shoes were custom made to have identical outsole tread geometry but with different levels of material hardness (F1, F2, F3). All sixty-three footwear were US size 9 men's shoe or the equivalent size for women's shoes.

Table 1. List of slip-resistant shoes included in the study from different brands (Rows that are bold represent modified shoes)

Shoe Code	Brand	Model	Style/item #	Style	Gender
A1	Shoes for Crews	Cambridge	6006	Dress	M
A2		Condor	24734	Athletic	M
A3		Delray - Canvas	38852	Casual	M
A4		Creed	21771	Athletic	M
A5		Senator	1201	Dress	M
A6		Avery	34545	Athletic	F
A7		Old School Low-Rider IV - Leather	39362	Casual	F
A8		Heather	9048	Athletic	F
<b>A2HS</b>		<b>Condor</b>	<b>24734</b>	<b>Athletic</b>	<b>M</b>
<b>A1HW</b>		<b>Cambridge</b>	<b>6006</b>	<b>Dress</b>	<b>M</b>
<b>A1CA</b>		<b>Cambridge</b>	<b>6006</b>	<b>Dress</b>	<b>M</b>
<b>A1SF</b>		<b>Cambridge</b>	<b>6006</b>	<b>Dress</b>	<b>M</b>
B1		Tredsafe	Axel	555307251	Athletic
B2	Executive II		553701356	Work	M
B3	Mario		553996011	Athletic	M
B4	Engage		565589700	Casual	U
B5	Kitch Canvas		553926483	Work	U
B6	Rig		553802532	Casual	U
B7	Nitro		556595638	Athletic	M
B8	Bailey		553987412	Athletic	W
<b>B1HS</b>	<b>Axel</b>		<b>555307251</b>	<b>Athletic</b>	<b>M</b>
<b>B1HW</b>	<b>Axel</b>		<b>555307251</b>	<b>Athletic</b>	<b>M</b>
<b>B1CA</b>	<b>Axel</b>		<b>555307251</b>	<b>Athletic</b>	<b>M</b>
<b>B1SF</b>	<b>Axel</b>		<b>555307251</b>	<b>Athletic</b>	<b>M</b>
C1	SR Max		Arlington	SRM350	Dress Oxford
C2		Tampa	SRM125	Athletic Oxford	F

C3		Abilene	SRM400	Casual Oxford	F
C4		Portland	SRM621	Skate	F
C5		Maxton	SRM620	Athletic	F
C6		Fairfax	SRM1580	Low Athletic	M
C7		Rialto	SRM6000	Athletic Sneaker	M
C8		Atlanta	SRM3700	Oxford	M
<b>C2HS</b>		<b>Tampa</b>	<b>SRM125</b>	<b>Athletic Oxford</b>	<b>F</b>
<b>C1HW</b>		<b>Arlington</b>	<b>SRM350</b>	<b>Dress Oxford</b>	<b>F</b>
<b>C1CA</b>		<b>Arlington</b>	<b>SRM350</b>	<b>Dress Oxford</b>	<b>F</b>
<b>C1SF</b>		<b>Arlington</b>	<b>SRM350</b>	<b>Dress Oxford</b>	<b>F</b>
D1	safeTstep	Deidre	162446	Oxfords	F
D2		Camina	159959	Runner	F
D3		Andre	173851	Court	F
D4		Kandice	163896	Canvas Oxfords	F
D5		Blast	159961	Runner	F
D6		Zeus	174484	Athletic	M
D7		Monroe	160023	Oxfords	M
D8		Halfpipe	166413	Canvas Oxfords	M
<b>D1HS</b>		<b>Deidre</b>	<b>162446</b>	<b>Oxford</b>	<b>F</b>
<b>D1HW</b>		<b>Deidre</b>	<b>162446</b>	<b>Oxford</b>	<b>F</b>
<b>D1CA</b>		<b>Deidre</b>	<b>162446</b>	<b>Oxford</b>	<b>F</b>
<b>D1SF</b>		<b>Deidre</b>	<b>162446</b>	<b>Oxford</b>	<b>F</b>
E1	Dr. Scholl's	Proudest	88626	Oxford	M
E2		Intrepid	88622	Sneaker	M
E3		Aiden	25311	Work Sneaker	M
E4		Roberts	14064	Oxford	M
E5		Hiro	25318	Oxford	M
E6		Kimberly II	88755	Sneaker	F
E7		Brave	88751	Sneaker	F
E8		Inhale	22876	Sneaker	F
<b>E2HS</b>		<b>Intrepid</b>	<b>88622</b>	<b>Sneaker</b>	<b>M</b>
<b>E1HW</b>		<b>Proudest</b>	<b>88626</b>	<b>Oxford</b>	<b>M</b>
<b>E1CA</b>		<b>Proudest</b>	<b>88626</b>	<b>Oxford</b>	<b>M</b>
<b>E1SF</b>		<b>Proudest</b>	<b>88626</b>	<b>Oxford</b>	<b>M</b>
F1	Timberland PRO	PRO-232	54.2±2.3 <sup>Ψ</sup>	Work	M
F2		PRO-232	60.4±1.5 <sup>Ψ</sup>	Work	M
F3		PRO-232	63.2±2.4 <sup>Ψ</sup>	Work	M

Ψ shore A hardness

HS modified to control heel shape

**HW** modified to control heel width  
**CA** modified to control tread surface area  
**SF** modified to control shape factor

Footwear outsole features such as material hardness [38, 40], tread surface area [40, 44], heel width [40] and heel shape [45] were selected for measurements based on their association with hysteresis friction from previous research. Additionally, shoe outsole metrics were selected to be low-cost in order to make the assessment accessible to practitioners (Table 2). For instance, a dynamic mechanical analyzer provides viscoelastic properties of elastomers [46], which may be linked to hysteresis friction [46, 47]. However, a mechanical dynamic analyzer may cost over \$10,000 whereas a Shore A durometer costs about \$30 (Table 2). Additionally, shape factor (i.e., the loaded area of a rubber block divided by its area of lateral surface free to bulge) was considered since shape factor has been found to affect the deformability of the rubber block in other tribology applications (elastomeric bearings and tire tread) subjected to vertical loading [48, 49]. We hypothesized that the shape factor of the individual tread will affect the ACOF since it influences the deformability of the tread.

Table 2. Experimental setup required for measurement of shoe outsole, floor surface and lubricant properties. The parameters included in this study are italicized (Tread depth was incorporated in the calculation of shape factor).

Parameters	Apparatus	Cost (U.S. dollars)*
Shoe outsole		
<i>Heel shape (sagittal plane)</i>	Visual observation	NA
<i>Heel width (frontal plane)</i>	Ruler <sup>1</sup>	\$5
<i>Material hardness</i>	Shore A durometer <sup>2</sup>	\$30
Mechanical properties	Dynamic Mechanical Analyzer <sup>3§</sup>	\$10,000
Surface roughness	Stylus profilometer <sup>4</sup>	\$1,500
<i>Tread depth</i>	Digital caliper <sup>5</sup>	\$10
<i>Tread surface area (top)</i>	Shoe imprint using ink pad <sup>6</sup>	\$10
Lubricant		
Viscosity	Rotary Viscometer <sup>7</sup>	\$500
Floor		
Surface roughness	Stylus profilometer <sup>4</sup>	\$1,500
Shoe-floor-lubricant		
Contact area/pressure	Pre-scale pressure sensitive film <sup>8</sup>	\$500
Surface free energy	Contact angle meter <sup>9</sup>	\$1,000

\* Actual costs vary according to brand, vendor, and exact device that is purchased

§ Price based on used equipment

<sup>1</sup>[50]

<sup>2</sup>[51]

<sup>3</sup>[52]

<sup>4</sup>[53]

<sup>5</sup>[54]

<sup>6</sup>[55]

<sup>7</sup>[56]

<sup>8</sup>[57]

<sup>9</sup>[58]

The Shore A material hardness of five different treads per shoe was measured using a durometer [59]. A mass of 1 kg was affixed and centered on the axis of the indenter as recommended by the ASTM [59] to improve repeatability of handheld measurements and additionally shoes were secured using a bench vise during measurements. The tread surface area of the heel was measured using an ink pad, a white blank sheet of paper and a scanner [36, 40]. Ink was applied to the outsole and the outsole was firmly pressed over a white blank sheet of paper. At least three imprints per shoe were created to ensure that pressure was applied across the entire heel section of the outsole and the heel imprint that had the maximum inked area was selected. The heel imprint was scanned and a MATLAB script (MATLAB, MathWorks®, Natick, MA) was developed to calculate the tread surface area (black region, Figure 1). The posterior-most point of the tread to 5 cm anterior of that point was used for calculation of the tread surface area (Figure 1)[40]. The heel width and dimensions of the tread blocks were measured using a ruler and digital caliper, respectively. The heel width was measured 1.5 cm anterior of the posterior-most point of the tread (Figure 1) [40]. Shoe beveling features were observed by placing the shoe on a level surface. The heel of the outsole was categorized as flat-edge or beveled edge if the heel was parallel to the level surface or formed a convex shape with respect to the leveled surface, respectively. The shape factor (S) was calculated based on the tread geometry at five different locations (Eq. 1) [48]. If the shape of the tread geometry varied across the heel, only the shape of the tread geometry that was dominant in the 1.5 cm most posterior section of the tread was considered for shape factor calculation. The loaded area was defined as the top surface area of a tread that was subjected to the normal load and the surface area free to bulge was considered as the lateral surface area of a tread (Figure 2). Sipes, which are cuts and groves on the tread surface, were neglected during this calculation (Figure 2).

$$S = \frac{\text{Loaded area}}{\text{Surface area free to bulge}} \quad \text{Eq. 1}$$

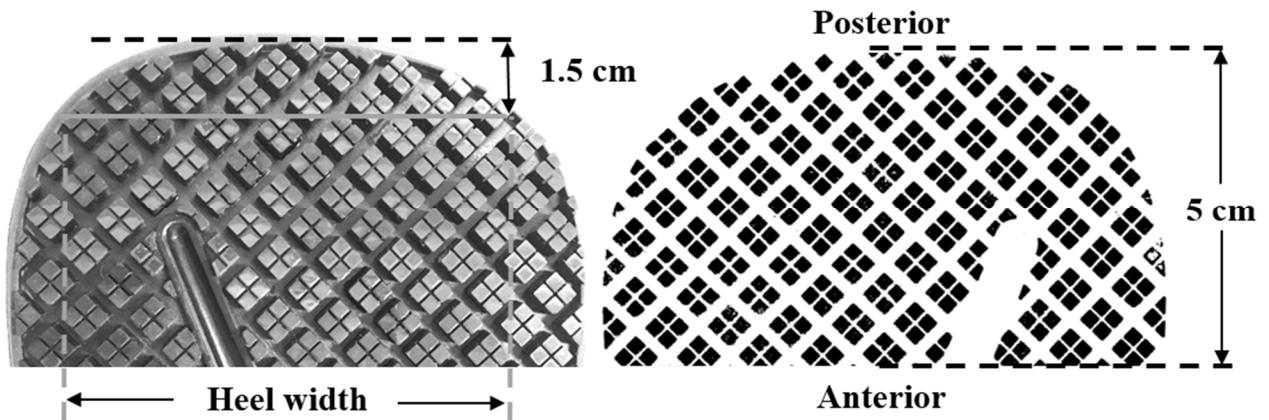


Figure 1. Heel width (left) and tread surface area (right) measurement

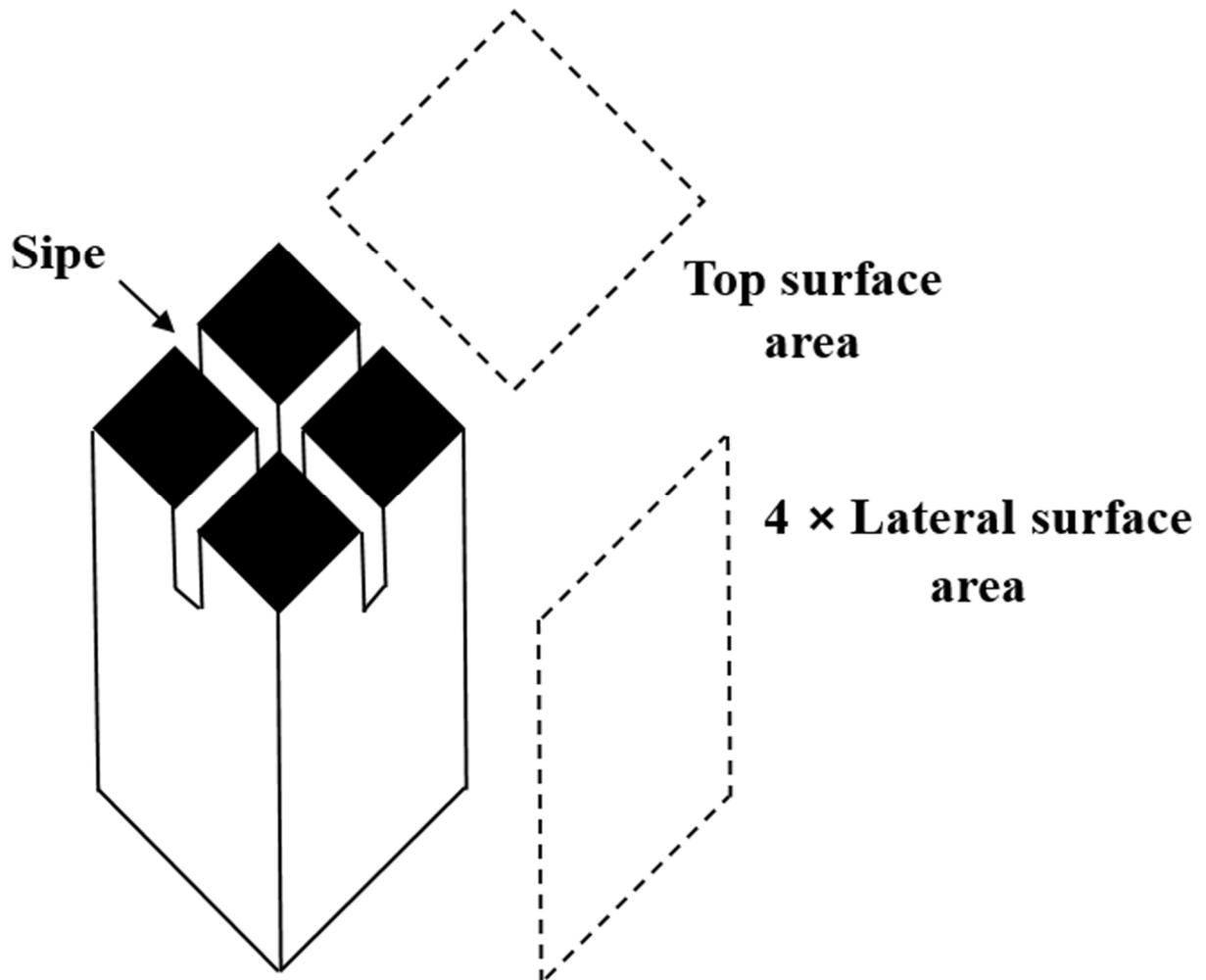


Figure 2. Shape factor measurement of a tread (black region represents tread surface area)

Four footwear from each brand (except Timberland PRO®) were altered to systematically vary tread surface area (A1CA-E1CA), heel width (A1HW-E1HW), shape factor (A1SF-E1SF) and heel shape (A2HS, B1HS, C2HS, D1HS, E2HS) within brands (Figure 3). (1) One flat-edge footwear per brand had tread removed at the midline (A1CA-E1CA). (2) One flat-edge footwear per brand had individual tread removed at the outer edge (A1HW-E1HW). (3) One beveled edge footwear had individual tread removed (A2HS, C2HS, E2HS) to approximate the heel width and tread surface area of the corresponding flat-edge footwear (A1, C1, E1) if the beveled edge had higher tread surface area than the flat-edge shoe. Otherwise the flat-edge shoe had tread removed (B1HS, D1HS) to closely match the heel width and tread surface area of the corresponding beveled edge footwear (B2, D2). (4) One flat-edge footwear per brand had tread depth shortened (about 1 mm) by abrasion on a belt sander with 36 grit belt (A1SF-E1SF). Modification 1 and 2 allowed for tread surface area and heel width to be systematically modified while keeping the heel shape, shape factor and material hardness consistent across shoes. Modification 3 allowed to discern the effect of heel shape while keeping the shape factor, material hardness, tread surface area and heel width consistent across shoes. Modification 4 modified the shape factor by decreasing the tread depth. Roughness measurements were taken after abrasion to monitor the surface roughness of the abraded shoes with respect to the new shoes. Five roughness measurements on five different treads were recorded for each shoe in

the direction of the shoe motion using a stylus profilometer (Surtronic S128, Taylor-Hobson®, AMETEK®, Leicester, United Kingdom). The scan length and cutoff frequency during roughness measurements of the tread surface were 1.6 mm and 0.8 mm, respectively. The abrasion caused significant changes to the shoe tread surfaces (A1SF-E1SF). The average peak to valley height ( $R_z$ ) for new shoes and abraded shoes (A1SF-E1SF) were  $13.2 \pm 5.7 \mu\text{m}$  and  $47.1 \pm 14.5 \mu\text{m}$ , respectively. The abraded shoes (A1SF-E1SF) were excluded *a priori* to the statistical analysis since surface roughness was a confounding factor with shape factor.

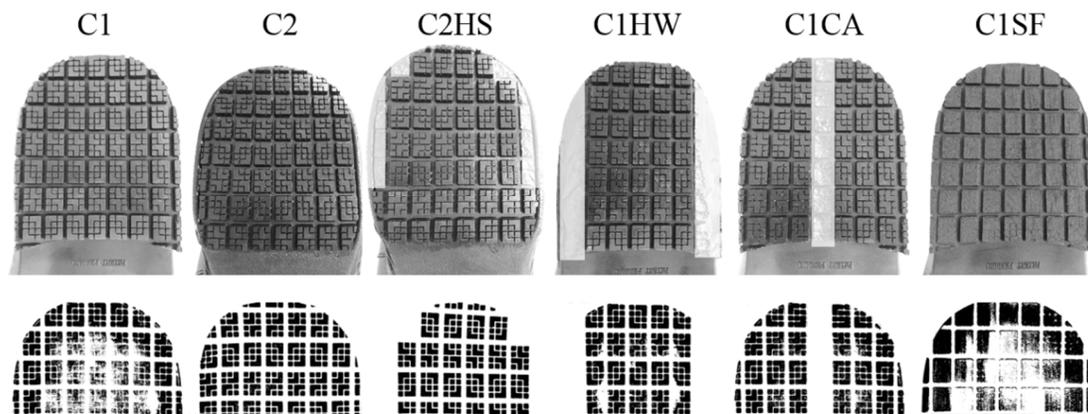


Figure 3. A representative set of shoe samples being modified and their corresponding tread surface area (Grey area on the shoe outsole represents regions where individual treads were removed).

The materials used for ACOF testing were canola oil and two floor designs. Canola oil was used as the liquid contaminant to simulate a common workplace contaminant in the service industry. A high and low traction tile were used for flooring condition: (1) ceramic tile (model: ADJF250802, make: ASTM), and (2) high pressure laminate tile (model: 00503 Stone Grafix, make: Formica®), respectively. Five roughness measurements were recorded for each tile in the direction of the shoe motion using the stylus profilometer. The scan length and cutoff frequency during roughness measurements were 8 mm and 0.8 mm, respectively. The average  $\pm$  standard deviation of the peak to valley height ( $R_z$ ), arithmetic average ( $R_a$ ), root mean square ( $R_q$ ), and root mean square of surface slope ( $R_{dq}$ ) for the ceramic/laminate tile were  $22.2 \pm 1.4 / 17.0 \pm 0.9 \mu\text{m}$ ,  $3.9 \pm 0.3 / 3.1 \pm 0.3 \mu\text{m}$ ,  $5.1 \pm 0.3 / 3.9 \pm 0.3 \mu\text{m}$ , and  $29.9 \pm 0.3 / 28.8 \pm 0.1^\circ$ , respectively. A total of 116 footwear-floor-contaminant combinations (58 footwear \* 1 liquid contaminant \* 2 floor surfaces) were tested.

#### E.2.1.1.2.ACOF Measurements:

A robotic friction measurement device, i.e. Portable Slip Simulator [24, 60], was used to measure the ACOF between the footwear outsole and floor surface in the presence of the contaminant. A 6 degree-of-freedom force plate (BERTEC Corporation, Columbus, OH, USA) with the floor tile mounted on top was used to record ground reaction forces with a sampling frequency of 500 Hz.

The ACOF testing parameters were an average normal force of  $250 \pm 10 \text{ N}$ , shoe-floor angle of  $17 \pm 1^\circ$  and sliding speed of 0.5 m/s. The 250 N,  $17^\circ$ , 0.5 m/s was selected based on the set of testing parameters that best predicted slip outcomes in a previous study [24]. The shoe-floor angle was measured when the shoe was fully loaded and forefoot was rotated to  $17^\circ$ . The shoe angle was with respect to the shoe's orientation when the shoe was unloaded and placed on the floor [40]. Five repeated trials were carried out for each shoe-floor combination.

### E.2.1.1.3. Data and Statistical Analysis:

The ACOF was quantified as the ratio of resultant shear force to normal force (Eq. 2) [61, 62]. The ACOF was averaged over the first 200 ms after the desired 250 N was achieved. The average normal force was within  $\pm 10$  N of 250 N and the range of normal force was within 10% (25 N) of 250 N during this 200 ms interval [24].

$$\text{ACOF} = \frac{\sqrt{F_{\text{Longitudinal Shear}}^2 + F_{\text{Transverse Shear}}^2}}{F_{\text{Normal}}} \quad \text{Eq. 2}$$

A multiple linear regression model was developed to predict ACOF in the presence of canola oil based on the tread features while controlling for the floor type. The independent variables were as follows: material hardness, tread surface area, heel width, shape factor, heel shape, floor type, and all first-order interactions. The heel shape and floor type were modeled as categorical variables.

The model's overall significance was tested using the F-test for multiple linear regression. Tests on individual regression coefficients (relative to zero) were performed using t-tests. A backward elimination method was used to screen the candidate regressors (predictors) and eliminate regressors (predictors) that have negligible effects. Additionally, forward selection and hybrid method were performed to determine if the model building approach influenced the parameters resulting in the model. A k-fold cross-validation method ( $k = 5$ ) was used to select the optimal model (i.e., to only select the predictors in the model that minimize the cross-validation error). The 5-fold cross-validation method was repeated five times for each model size since cross-validation error changes due to different split of data in the cross-validation folds. The model was selected based on the one-standard-error-rule (i.e., cross-validation error is within one standard error of the lowest point on the curve) [63]. The cross-validation method assessed how well the trained models predicted an independent data set. The advantage of the k-fold cross-validation is that each subset of data is used for both training (i.e., estimation) and testing (i.e., validation) [63]. Residual analysis was performed to ensure that the normality and homoscedasticity assumptions of the regression model were met. A Shapiro-Wilk test was used to test if the ACOF residuals from the model followed were following a normal distribution. The statistical analyses were performed using commercial software (JMP<sup>®</sup> Pro 14.0.0, SAS Institute Inc., Cary, NC, USA) with a significance level of 5%.

### E.2.1.2. Results

The shoes were evenly distributed between beveled edge (50%, 29 shoes) and flat-edge (50%, 29 shoes) heel shapes. The shore A hardness and shape factor values ranged from 44.2 to 65.6 and from 0.19 to 0.91, respectively. The tread surface area ranged from 6.36 to 16.08 cm<sup>2</sup> (same range without modified shoes). The heel width was between 3.8 cm and 7.4 cm (5.0 to 7.4 cm without the modified shoes). The ACOF values for the 43 shoes (excluding the modified shoe outsoles) with ceramic and laminate tile ranged from 0.283 (D7) to 0.710 (C7) and 0.127 (D7) to 0.413 (C8), respectively (Figure 4A-F). The ACOF for the 15 modified shoes ranged from 0.358 (E1CA) to 0.677 (C1HW) for ceramic tile and 0.197 (D1CA) to 0.385 (C2HS) for laminate tile, which were within the ACOF range of unmodified shoes on the corresponding floorings. All shoes had higher ACOF on ceramic tile compared to laminate tile (Figure 4).

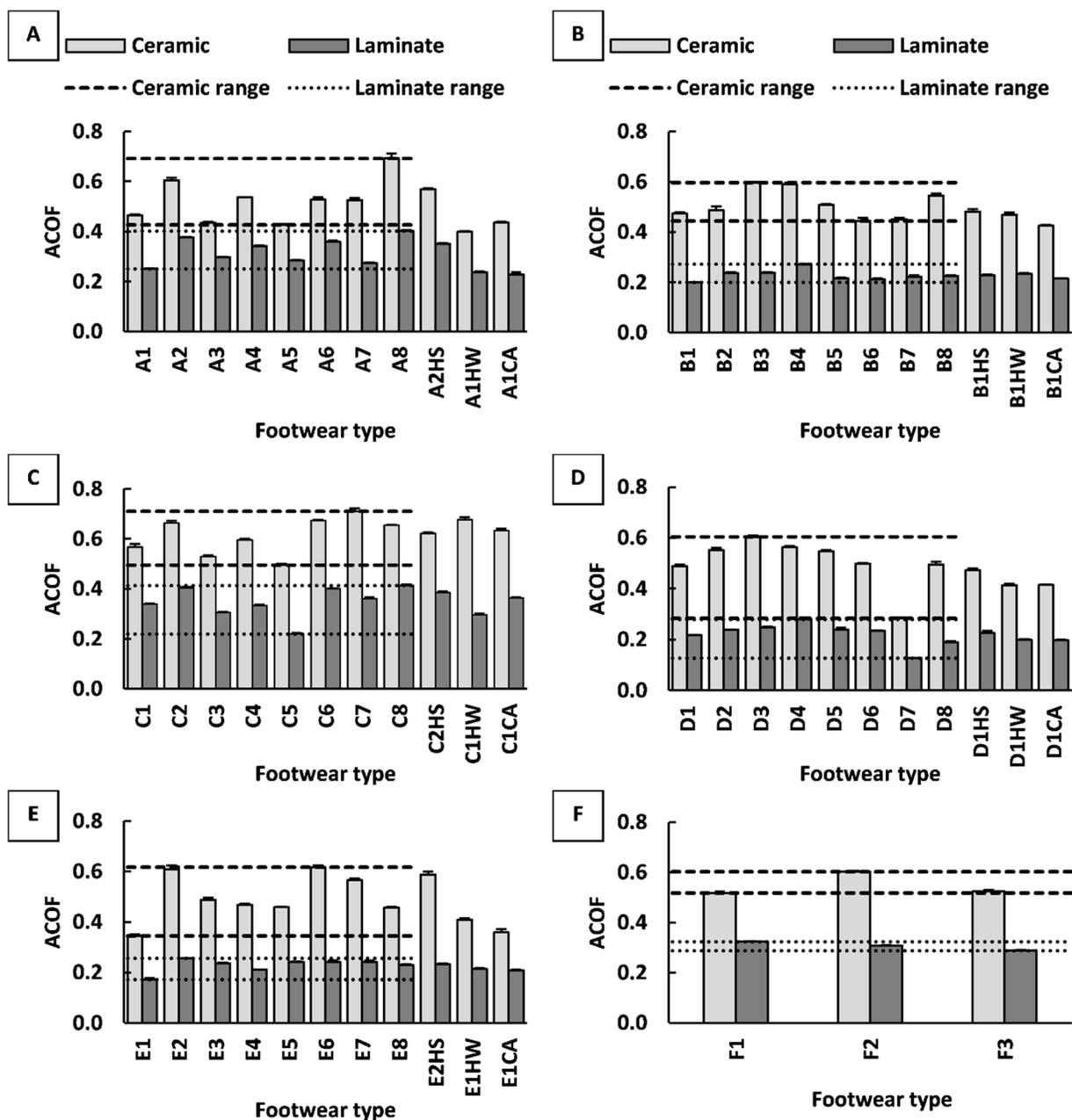


Figure 4. ACOF for ceramic (light grey) and laminate (dark grey) tile with canola oil for the shoe brands: (A) Shoes for Crews, (B) Tredsafe, (C) SR Max, (D) safeTstep, (e) Dr. Scholl's, and (F) Timberland PRO. The dashed lines and round dots on each plot show the range of ACOF within brands (for unmodified shoes) on both ceramic and laminate tile, respectively.

The ACOF was significantly predicted by the full model that included all predictors (material hardness, tread surface area, heel width, shape factor, heel shape, floor type, and all first-order interactions,  $F_{21,94} = 37.2$ ,  $p < 0.001$ ). The t-test performed on the individual regression coefficients indicated that the heel shape (beveled:  $t_{95} = 3.44$ ,  $p = 0.001$ ), tread surface area ( $t_{95} = 3.81$ ,  $p < 0.001$ ), hardness ( $t_{95} = -2.31$ ,  $p = 0.023$ ), floor type (ceramic:  $t_{95} = 25.08$ ,  $p < 0.001$ ), and the interaction between the heel shape and shape factor ( $t_{95} = -2.26$ ,  $p = 0.023$ ) were statistically significant. The heel width ( $t_{95} = -0.64$ ,  $p = 0.524$ ) and shape factor ( $t_{95} =$

1.36,  $p = 0.176$ ) were insignificant in the full model. This model explained 89% ( $R^2 = 0.893$ ,  $R^2_{adj} = 0.869$ ,  $RMSE = 0.054$ ) of the variation in ACOF based on the full set of predictor variables.

The backward elimination method resulted in a reduced model ( $F_{6,109} = 135.3$ ,  $p < 0.001$ , Eq. 3) and included the heel shape ( $t_{110} = 3.37$ ,  $p = 0.001$ ), tread surface area ( $t_{110} = 4.92$ ,  $p < 0.001$ ), hardness ( $t_{110} = -2.93$ ,  $p = 0.004$ ), shape factor ( $t_{110} = 3.15$ ,  $p = 0.002$ ), floor type ( $t_{110} = 25.73$ ,  $p < 0.001$ ), and the interaction between the heel shape and shape factor ( $t_{110} = -2.42$ ,  $p = 0.017$ ) (Table 3). The heel width and other first-order interactions were removed in the reduced model by the backward elimination method. The forward selection method resulted in a reduced model ( $F_{4,111} = 187.1$ ,  $p < 0.001$ , Eq. 4) that included four of the six factors that were part of the model identified through the backward elimination method. The model resulting from the forward selection method included the heel shape ( $t_{112} = 3.48$ ,  $p = 0.001$ ), tread surface area ( $t_{112} = 5.26$ ,  $p < 0.001$ ), hardness ( $t_{112} = -2.64$ ,  $p = 0.009$ ), and floor type ( $t_{112} = 24.86$ ,  $p < 0.001$ ) (Table 3). The heel width, shape factor and all first-order interactions were not added to the model via the forward selection method. The hybrid method resulted in the same model as the backward elimination method. A slightly lower standard error was achieved with 6 predictors (i.e. backward elimination model) than what was achieved with 4 predictors (i.e., forward selection model) (Figure 5). While the model with 6 predictors (Eq. 3) was considered the optimal model based on this criterion, the model with 4 predictors (Eq. 4) was nearly as strong, did not include any interaction effects, and required one fewer measurement. In Eq. , the units are represented in brackets for continuous variables. Nominal dummy variables are set to a value of 1 when the condition within the brackets is present and 0 when the condition within the brackets is not present. The predictor variables in the optimal/backward elimination model explained 88.2% ( $R^2 = 0.882$ ,  $R^2_{adj} = 0.875$ ,  $RMSE = 0.053$ ) of the variation in ACOF (Supplemental Figure 9). The forward selection model explained 87.1% ( $R^2 = 0.871$ ,  $R^2_{adj} = 0.866$ ,  $RMSE = 0.055$ ) of the variation in ACOF (Figure 6). The normal quantile plot for the backward (Supplemental Figure 10A) and forward model indicated no extreme violations of the normality assumption (Figure 7A). Additionally, the Shapiro-Wilk test indicated that the ACOF residuals follow a normal distribution ( $W = 0.985$ ,  $p = 0.224$ ). The plot of the residual vs. predicted ACOF did not exhibit any extreme unusual patterns that suggest violations of homoscedasticity assumption for either model (Figure 6B and Supplemental Figure 10B).

Backward elimination:

$$\text{ACOF} = 0.158 + 0.014 * \text{tread surface area [cm}^2\text{]} + 0.130 * \text{heel shape} - 0.003 * \text{hardness [Shore A]} + 0.160 * \text{shape factor} + 0.254 * \text{floor} - 0.154 * \text{heel shape} * \text{shape factor} \quad \text{Eq. 3}$$

Forward elimination:

$$\text{ACOF} = 0.223 + 0.015 * \text{tread surface area [cm}^2\text{]} + 0.041 * \text{heel shape} - 0.003 * \text{hardness [Shore A]} + 0.254 * \text{floor} \quad \text{Eq. 4}$$

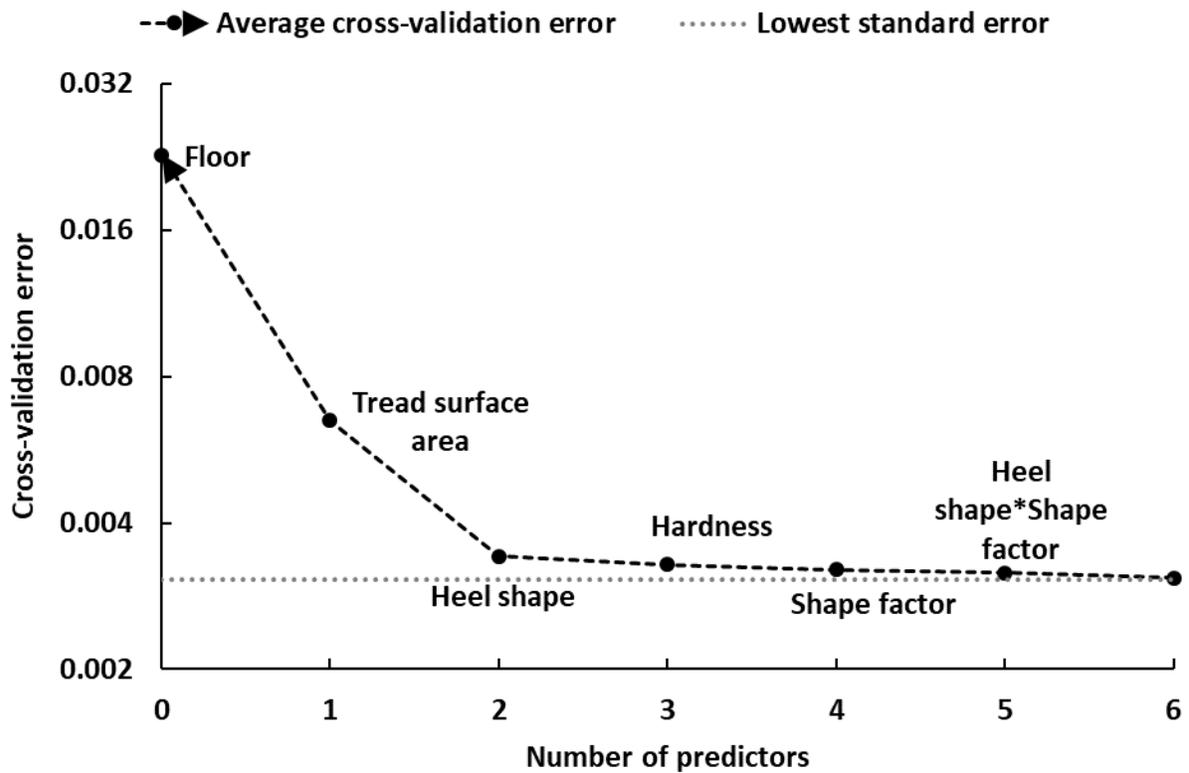


Figure 5. Cross-validation error for different number of significant predictors in the reduced models. The data label above/below each data point indicates which parameter was removed during backward elimination. Standard error for each data point is small, which is not visible on the plot.

Terms	Backward elimination			Forward selection		
	$\beta_0$ (CI)	Std error	t-test (p-value)	$\beta_0$ (CI)	Std error	t-test (p-value)
Intercept	0.158 (-0.003 to 0.320)	0.082	1.94 (0.055)	0.223 (0.064 to 0.383)	0.081	2.77 (0.007)
Heel shape[beveled]	0.130 (0.054 to 0.207)	0.039	3.37 (0.001)	0.041 (0.018 to 0.064)	0.012	3.48 (0.001)
Floor[ceramic]	0.254 (0.234 to 0.273)	0.010	25.73 (<.001)	0.254 (0.234 to 0.274)	0.010	24.86 (<.001)
Tread surface area (cm <sup>2</sup> )	0.014 (0.008 to 0.020)	0.003	4.92 (<.001)	0.015 (0.009 to 0.021)	0.003	5.26 (<.001)
Heel width (cm)	NA	NA	NA	NA	NA	NA
Shape factor	0.160 (0.059 to 0.261)	0.051	3.15 (0.002)	NA	NA	NA
Hardness	-0.003 (-0.005 to -0.001)	0.001	-2.93 (0.004)	-0.003 (-0.005 to -0.001)	0.001	-2.64 (0.009)
Heel shape[beveled]	-0.154 (-0.280 to -0.028)	0.064	-2.42 (0.017)	NA	NA	NA
*Shape factor	NA	NA	NA	NA	NA	NA
Other first order interactions	NA	NA	NA	NA	NA	NA

Table 3. Summary of parameter estimates (95% confidence interval: CI and standard error: Std error) for the backward elimination (column 2-4) and forward selection (column 5-7) model. NA represents variables that were not part of the model.

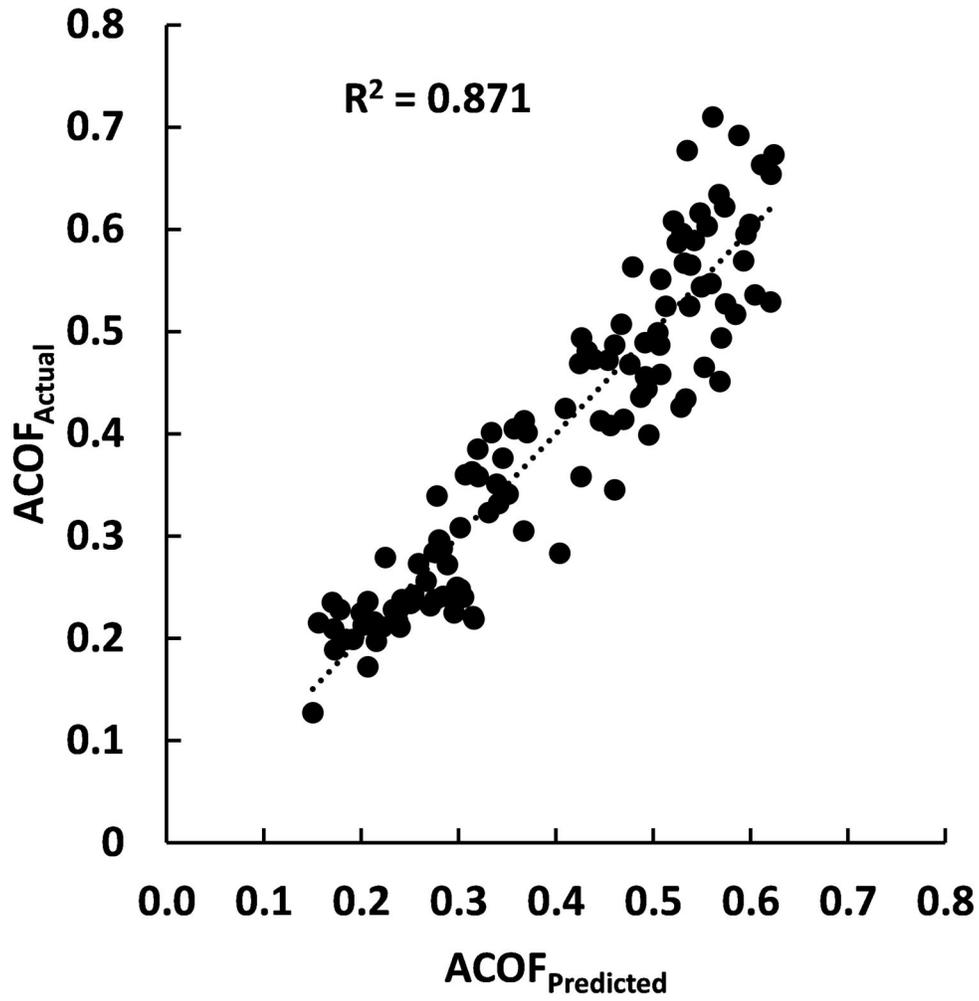


Figure 6. Actual vs. predicted ACOF (response variable) from the forward model (Eq. 4)

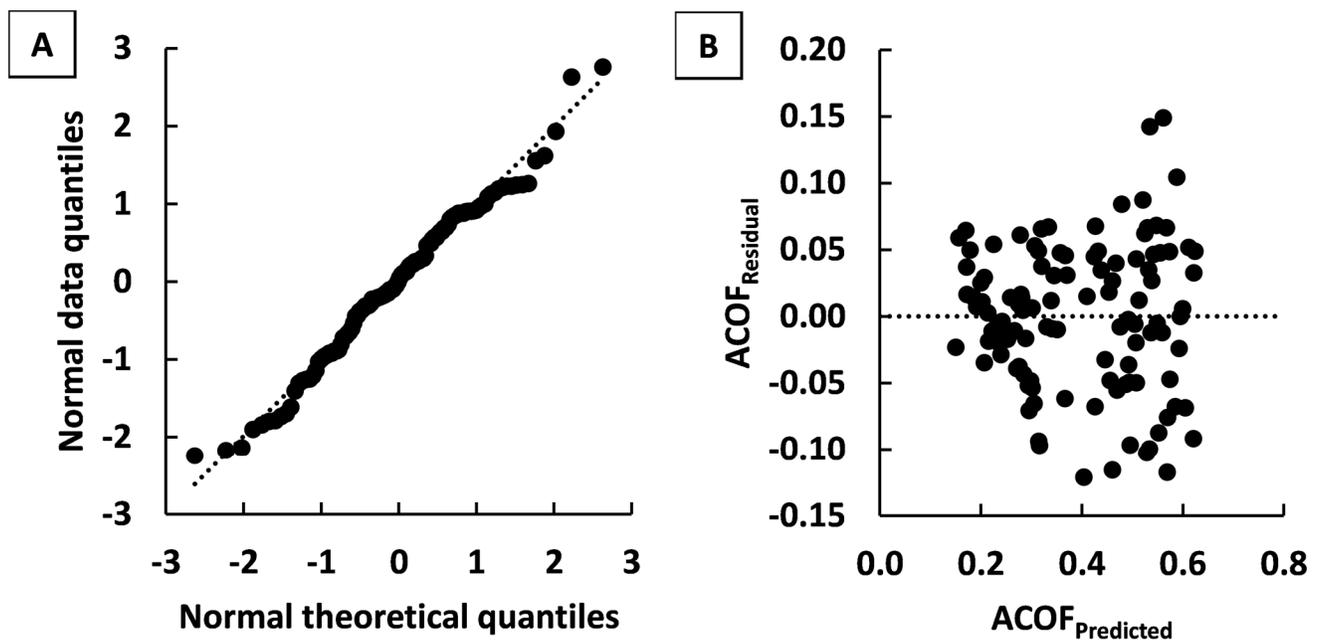


Figure 7. Residual analysis performed on forward model: (A) normal quantile plot to assess the assumption of normality; an (B) plot of residual vs. predicted ACOF to assess assumption of homoscedasticity.

According to the regression coefficients from the forward model (Table 3), a unit increase in the tread surface area ( $\text{cm}^2$ ) increased the ACOF by 0.015 ( $\beta_{\text{Tread surface area}}$ ). An increase in the tread surface area from the first quartile (9.6) to the third quartile (13.4) increased ACOF by 0.057 (interquartile range \*  $\beta_{\text{Tread surface area}} = 3.8 * 0.015$ ). A unit increase in the Shore A hardness decreased the ACOF by 0.003 ( $\beta_{\text{Hardness}}$ ). An increase in the Shore A hardness from the first quartile (49.8) to the third quartile (60.8) reduced ACOF by 0.033 (interquartile range \*  $\beta_{\text{Hardness}} = 11.0 * -0.003$ ). The change from flat-edge to beveled edge heel shape increased ACOF by 0.041 ( $\beta_{\text{Heel shape[beveled]}}$ ). The change of floor type from laminate to ceramic tile added 0.254 ( $\beta_{\text{Floor[ceramic]}}$ ) to the ACOF.

### E.2.1.3. Discussion

The main finding of this study was that simple and relatively inexpensive measurements of footwear outsole tread could predict the variation in oily traction performance across shoes labeled as slip-resistant. This finding indicated that tread geometry (heel shape and tread surface area) and material hardness, while controlling for floor type, explained 87% of the variation in oily ACOF. Change in heel shape from flat to beveled edge and increase in tread surface area were favorable in the traction performance within each brand. Moreover, the prediction of ACOF was based on mostly main effects. Only a single interaction term (heel shape\*shape factor,  $p$ -value = 0.017) was observed and this interaction effect was only observed in two of the three stepwise regression models. These findings have two-fold benefits. First, assessment of slip-resistant shoes based on regression model predictions will be possible for safety practitioners without actually performing experimental shoe traction testing. Second, footwear manufacturers can improve shoe traction by prioritizing heel shape (flat to beveled edge) and tread surface area.

The relationship between shoe outsole tread, floor type, and ACOF in the current study are generally in agreement with previous research. The tread surface area was positively associated with ACOF, consistent with previous findings [40, 44]. As the tread surface area increases, contact pressures reduce and consequently cause an increase in hysteresis friction [44]. The higher ACOF

values associated with beveled edge heel shape compared to flat edge were also consistent with findings of Moghaddam and Beschorner [45]. A beveled edge increases the area of contact by conforming the tread to the floor when the shoe is at an angle during the early stages of stance. This has a positive impact on ACOF. The effect of material hardness on ACOF has been also supported by previous research [10, 38, 40, 64] since hardness contributes to hysteresis friction in the presence of high viscous lubricants [10, 64]. The softer elastomer (low hardness level) will be subjected to higher deformation compared to the harder material, which increases ACOF [10]. Furthermore, the floor surface with a higher roughness was associated with a higher ACOF, which has been demonstrated in previous research [42, 64, 65].

The statistical model predicting footwear traction based on simple and inexpensive measurements of outsole tread may be a useful assessment tool. Tread surface area was measured with an ink pad, paper and scanner. Heel shape was visually observed without the use of any equipment. Hardness was measured using a durometer that costs approximately US \$30 (Table 1). A safety manager could measure these parameters and use the developed model to screen out slip-resistant shoes that pose a high or moderate slip risk. For instance, the model differentiated between shoes with high and low ACOF across brands similar to the ACOF yielded through experiments (Figure 8). The study revealed that certain shoes with low ACOF show evidence of poor outsole backing design that result in gaps in tread surface area compared with other designs within the same brand (Figure 8, left). Thus, the observational methods described in this study may help to differentiate across shoes with higher and lower slip-resistant properties. About 70% of unmodified shoes tested on laminate tile had ACOF below 0.30. An ACOF level above 0.30 [66] or 0.29 [67] has been suggested for safe level walking. Furthermore, the range of ACOF values (0.127-0.413) for laminate tile had overlap with RCOF range (0.155-0.272) for level walking [68-70]. Furthermore, recent research has demonstrated that interventions that only permit high performance slip-resistant shoes can dramatically reduce the odds of slipping compared with interventions where employees can select any slip-resistant footwear [20]. Thus, this study operated in conditions where the differences in shoe performance are relevant and where identifying high performance slip-resistant shoes could reduce fall injuries.

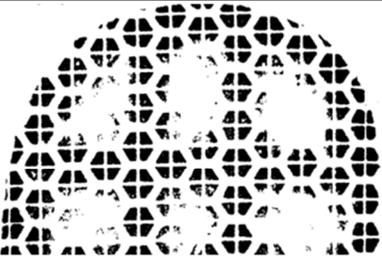
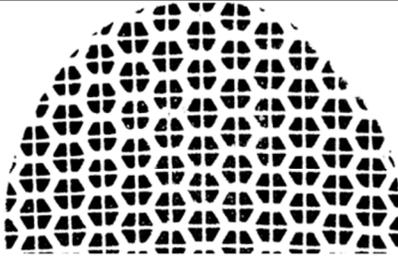
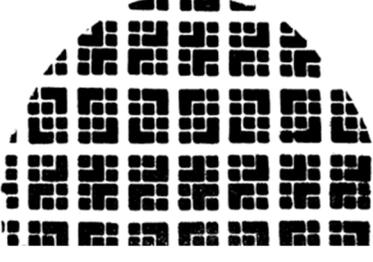
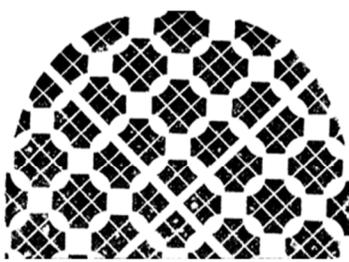
	Flat	Beveled	
<b>B1</b>	 <p>A = 9.1 cm<sup>2</sup>, H = 64.4±1.8 ACOF<sub>Actual(Predicted)</sub> = 0.199(0.185)</p>	<b>B4</b>	 <p>A = 12.5 cm<sup>2</sup>, H = 60.2±1.1 ACOF<sub>Actual(Predicted)</sub> = 0.272(0.289)</p>
<b>C1</b>	 <p>A = 12.8 cm<sup>2</sup>, H = 50.8±0.8 ACOF<sub>Actual(Predicted)</sub> = 0.339(0.278)</p>	<b>C8</b>	 <p>A = 16.0 cm<sup>2</sup>, H = 50.8±2.8 ACOF<sub>Actual(Predicted)</sub> = 0.413(0.367)</p>
<b>D7</b>	 <p>A = 6.4 cm<sup>2</sup>, H = 62.0±3.3 ACOF<sub>Actual(Predicted)</sub> = 0.127(0.150)</p>	<b>D3</b>	 <p>A = 13.4 cm<sup>2</sup>, H = 60.4±4.8 ACOF<sub>Actual(Predicted)</sub> = 0.248(0.302)</p>

Figure 8. A comparison of ACOF across heel designs within brands (B, C, D) on laminate tile. ACOF is labeled for the measured value (Actual) as well as the model-predicted value (Predicted) based on Eq. 4 (forward model). The ACOF is relatively higher for the designs in column one (B4, C8, D3) compared to their corresponding shoe brand (B1, C1, D7) in column two primarily due to higher tread surface area and beveled edge heel shape. (A and H represent tread surface area and Shore A hardness, respectively.)

Certain limitations of the current study should be acknowledged. Only two different floorings were utilized and flooring was treated as a categorical variable in the regression analysis instead of by its physical characteristics. Future research that incorporates physical characteristics of flooring such as multiscale surface roughness [44] and spreading coefficient [71, 72] into the statistical model to

predict traction would be beneficial. It is worth noting that interaction effects including flooring were small and insignificant. Furthermore, other research has suggested that shoe traction performance across vinyl composite, quarry and ceramic floor surfaces are generalizable in the presence of canola oil [73]. Thus, these results are expected to be consistent when applied to other floorings. Moreover, the liquid contaminant used was canola oil which allowed this study to focus primarily on hysteresis friction mechanisms within boundary lubrication. Further investigations are required to understand the generalizability to other liquid contaminants such as water and detergent aqueous solution. Another limitation is that this model should not be used to predict ACOF beyond the range of predictors that were used to develop the model (Shore A hardness: 44.2-65.6; shape factor: 0.19-0.91, heel shape: flat or beveled edge, tread surface area: 6.36-16.08 cm<sup>2</sup>). This study only included shoes with tread that were presumed to operate in boundary conditions and may not be applicable to non-slip resistant or worn shoes that may operate in other lubrications regimes like hydrodynamic lubrication [32, 33]. Lastly, the model may not be applicable to foot slips on ladder rung, stair and during fast walking or running conditions.

In summary, the current study suggests that slip-resistant shoes with a beveled heel shape, higher tread surface area, and lower material hardness generate higher traction in the presence of canola oil. Furthermore, a multiple regression model was generated that predicted ACOF based on these parameters. This type of predictive model may be useful to safety practitioners to select higher traction performance shoes.

#### E.2.1.4. Supplemental Figures

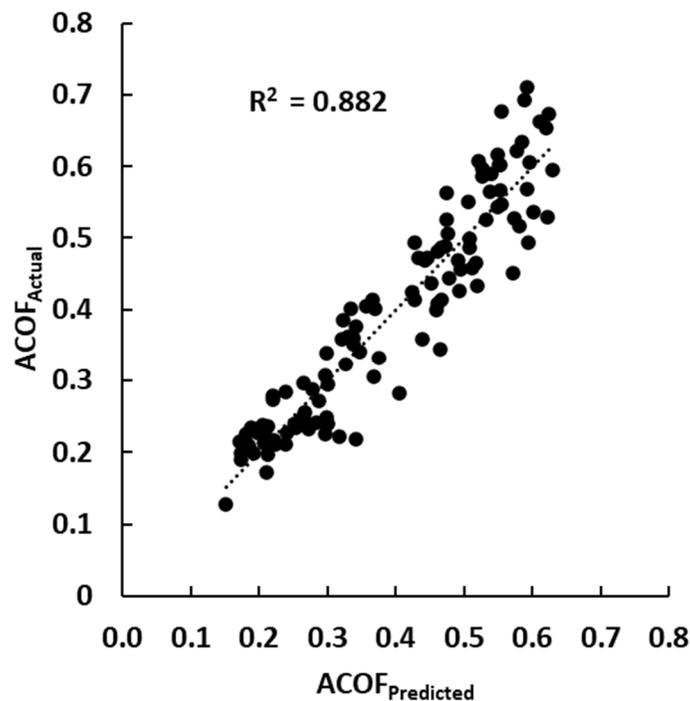


Figure 9. Actual vs. predicted ACOF (response variable) from the backward model (6 predictors).

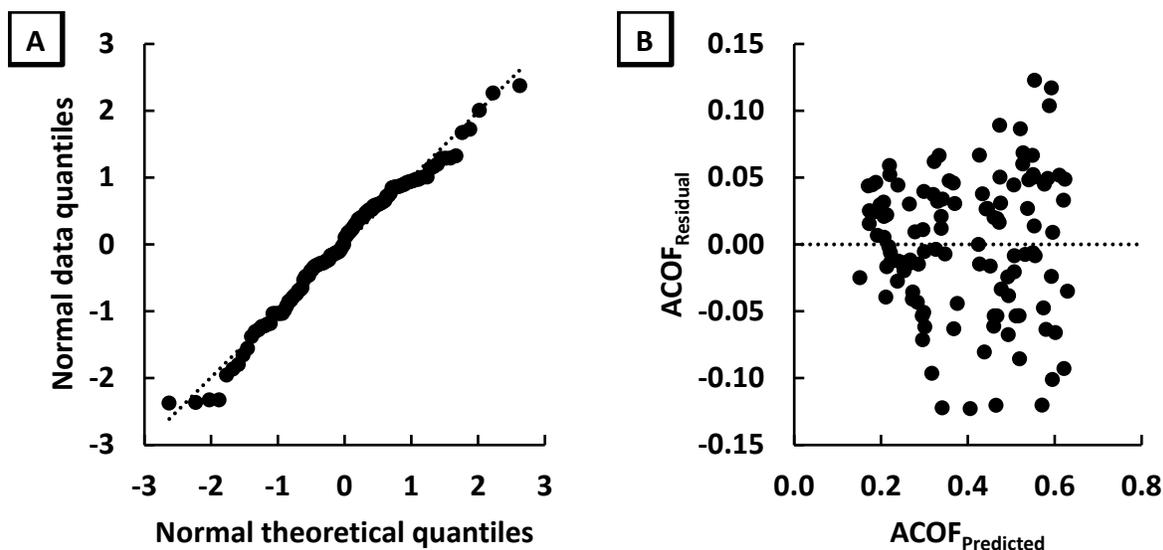


Figure 10. Residual analysis performed on the backward model: (A) normal quantile plot to assess the assumption of normality; and (B) Plot of residual vs. predicted ACOF to assess assumption of homoscedasticity.

### E.2.2. Aim #1, Study #2: In contrast to slip-resistant shoes, fluid drainage capacity explains friction performance across shoes that are not slip-resistant [confidential]

The purpose of this study is to quantify whether a predictive regression model developed for SR shoes (based on the tread surface area, shoe beveling, and hardness) [74] similarly applies to NSR shoes. We hypothesize that this model will predict COF for NSR shoes similar to the SR shoe predictions. In addition, we also predict that fluid pressure will contribute to shoe-floor friction.

#### E.2.2.1. Methods

To achieve the purpose of this study, ACOF and shoe tread parameter data (tread surface area, hardness, and heel beveling) from a previous study on SR shoes [74] was combined with newly collected data on NSR shoes. Data collected for NSR shoes included ACOF, shoe tread parameter data (tread surface area, shoe beveling, and hardness), and under-shoe fluid pressures.

##### E.2.2.1.1. Selection of shoes

A total of 15 common NSR shoes were selected (Table 4). These shoes were from three different styles: athletic ( $n = 5$ ), dress ( $n = 5$ ), and comfort ( $n = 5$ ). The shoes were selected from five major online footwear retailers (annual revenue for 2019): Amazon and its subsidiary Zappos, (\$3.9 billion), Macy's (\$940 million), Foot Locker (\$680 million), and ShoeBuy (\$510 million). Online retail sites were used instead of physical retail stores because online sites commonly advertise the shoes that are the most popular. These vendors were chosen because they collectively accounted for 40% of the online shoe retail market. More NSR shoes were chosen from Amazon (and its subsidiary Zappos) than the other vendors as these companies hold a higher market share. Shoes were selected from October 2018 to January 2019 according to each website's best-seller list. The list of selected shoes, vendors, style, and gender label is presented in Table 4. High heel shoes were excluded from this study since they influence gait patterns [75] and the friction testing methods were validated for slips in non-heeled shoes [24].

Table 4. List of selected NSR shoes from online vendors. For Gender, the following codes were used based on the manufacturer's description: M: Men's, W: Women's, U: Unisex

Shoe Code	Online Vendor	Shoe Name	Style	Gender
NSR1	Amazon	New Balance 608-4	Athletic	M
NSR2	Amazon	Asics Gel-Venture 6	Athletic	M
NSR3	Amazon	Brooks Adrenaline GTS 1	Athletic	W
NSR4	ShoeBuy	Skechers D'Lites	Athletic	W
NSR5	Footlocker	Adidas Original Superstar	Comfort	W
NSR6	Macy's	Converse Chuck Taylor	Comfort	W
NSR7	Zappos	Asics Gel Nimbus 20	Athletic	W
NSR8	Amazon	Puma Suede	Comfort	W
NSR9	Amazon	Dockers Gordon Leather	Dress	M
NSR10	Amazon	Clarks Tilden Cap Oxford	Dress	M
NSR11	Zappos	Rockport Margin Oxford	Dress	M
NSR12	ShoeBuy	Keds Champion Leather	Comfort	W
NSR13	Zappos	Vans Old Skool	Comfort	U
NSR14	Zappos	Franco Sarto Bocca	Dress	W
NSR15	Zappos	Dansko	Dress	W

#### E.2.2.1.2. Collection of Data using Lab Equipment

ACOF and peak under-shoe fluid pressure were measured, while a mechanical device simulated the dynamics of slipping. The slip tester was modelled after the portable slip simulator [24, 60]. The slip tester has three vertical motors and one horizontal motor. These motors were responsible for translating the shoe at 0.5 m/s and applied a force of 250 N [24]. A shoe angle of  $17 \pm 1$  degree was controlled with an adjustable bracket and was verified during testing with a goniometer. These testing methods reflect the dynamics of slipping and are predictive of human slips [24, 62]. The flooring was attached to a force plate (BERTEC Corporation, Columbus, OH, USA), which sampled at a frequency of 500 Hz. Five trials were collected and the ACOF across these five trials was averaged. The ACOF measurements were collected with an oil contaminant on two flooring materials, ceramic [76] and laminate (used in [77]). These surface materials are commonly found in commercial flooring and represent a polymer-based and a clay-based material. In the presence of oily conditions, good correlation has been observed across polymer and clay-based materials [73, 78]. Thus, results from these conditions are expected to be applicable to a wide-range of common flooring materials.

To measure the peak fluid pressure, the floor surface was instrumented with four pressure transducers (Setra, 3100R100PG089, Boxborough, MA, USA). The transducers were placed 25 mm

apart. Between each of the five trials, the floor was moved 5 mm with respect to the shoe in the direction transverse to the long axis of the shoe. Overall, this led to 20 scans (4 scans per trial x 5 trials) at 5 mm intervals to capture fluid pressures across the surface of the shoe (Figure 11). In the direction of foot sliding, the pressure transducers were placed so that the shoe passed them at half of the slip distance after the target normal force was reached. Fluid pressure was only collected on the laminate flooring because the thickness of the ceramic floor would have led to a substantial gap between the transducer and floor surface. Because fluid pressure is largely sensitive to the shoe features [77, 79], similar trends were expected for ceramic flooring as the laminate flooring. Fluid pressure data were sampled at 500 Hz.

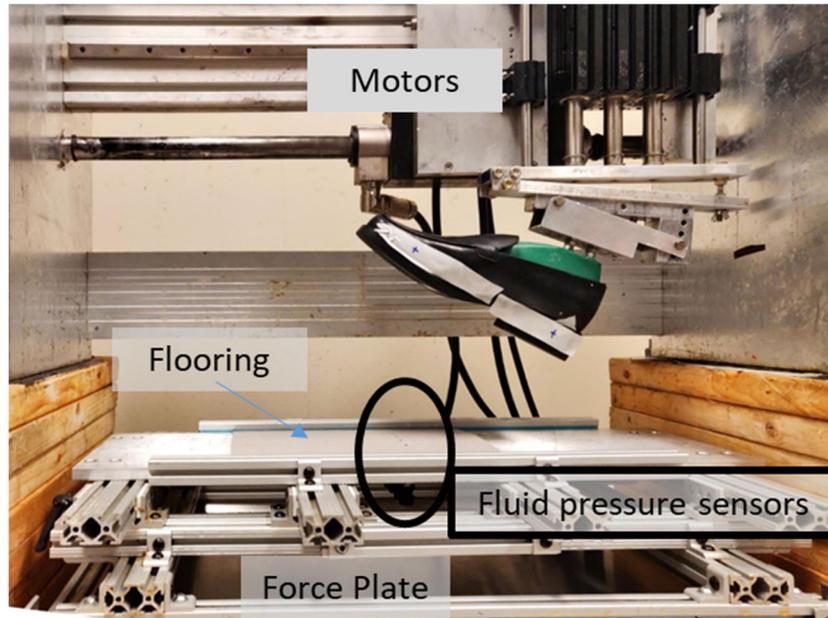


Figure 11. Portable Slip Tester fitted with the fluid pressure extension (location of pressure sensors shown in oval).

#### E.2.2.1.3. Collection of NSR shoe parameters

The parameters of tread surface area, hardness, and heel shape were collected since they are known to affect ACOF in SR shoes [40, 74]. To measure tread surface area, the sole of each NSR shoe was coated with ink and transferred to white paper (Figure 12). This paper was then scanned and converted to a black and white image (spatial resolution of 0.042 mm). The tread surface area of the heel was measured as the summed black pixel area for the 50 mm most posterior portion of the shoe [40, 74]. The back 50 mm of the sole was used in this calculation because this area represents the majority of the shoe region where fluid pressures are observed [33].

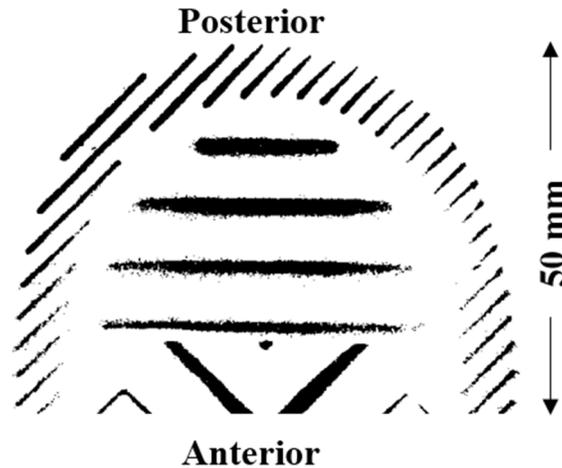


Figure 12. Scanned ink imprint of a NSR shoe (NSR 6).

To measure hardness, a durometer (Shore A durometer based on ASTM standard D2240, 2015) was used. The outsole of the shoe was held flat by a clamp, and a mass of 1 kg was placed on the durometer to improve the accuracy of the hardness readings [74]. The hardness readings were recorded and averaged across five different locations of the 50 mm of the posterior portion of the shoe. The final parameter, heel shape, was classified as either flat or beveled based on observation. Flat shoes were characterized by a heel that touched the floor with no pressure applied. Shoes with a round or chamfer in the sagittal plane were categorized as beveled [45]. Beveling was assessed since it has been found to increase ACOF in SR shoes [74].

#### E.2.2.1.4. Data and Statistical Analysis

The ACOF was calculated based on the longitudinal shear force, transverse shear force, and the normal force (Eq. 5). These forces were based on the 200 ms after the normal force reached 250 N. The peak fluid pressure was calculated as the maximum value across the four fluid pressure sensors and over the five trials [80].

$$ACOF = \frac{\sqrt{F_{Longitudinal\ Shear}^2 + F_{Transverse\ Shear}^2}}{F_{Normal}} \quad \text{Eq. 5}$$

The predicted ACOF was calculated for each of the NSR shoes based on regression equations developed in Iraqi et al. [74]. These regression equations are based on the forward selection model that was deemed to be the preferred model in that study. This model predicts ACOF as a function of tread surface area, heel bevel, hardness, and the flooring (Eq. 6), where the number in the brackets represents the unit of measure or the dichotomous state of the parameter (e.g., the heel shape variable is 1 for beveled shoes and 0 for non-beveled shoes). The measurement methods for tread parameters and the floor samples were identical in this study to the ones described in Iraqi et al. [74].

$$ACOF = 0.223 + 0.015 * \text{tread surface area [cm}^2\text{]} + 0.041 * \text{heel shape [bevel]} - 0.003 * \text{hardness [Shore A]} + 0.254 * \text{floor [ceramic]} \quad \text{Eq. 6}$$

Statistical analyses were conducted to assess: 1) whether the model previously developed for SR shoes similarly applies to NSR shoes; and 2) to determine whether fluid pressures contribute to

friction among NSR shoes (JMP 15.2, Cary, NC, USA). An alpha value of 0.05 was used for all analyses. The research questions presented within this paper were consistent with the planned analyses prior to data collection.

A Wilcoxon signed-rank test was performed to determine if the measured ACOF values differ significantly from the predicted ACOF based on the model for SR shoes. This method was used because the data was bimodal and trended toward not being normally distributed ( $W=0.94$ ;  $p = 0.070$ ). The Wilcoxon Signed-Rank Test makes no assumptions about the data distribution and is considered a conservative test since it errors towards controlling Type 1 error. The null hypothesis was that the difference between the actual and predicted friction values was 0 (the predicted values do not systematically overestimate or underestimate ACOF for NSR shoes). The purpose of this analysis was to determine if a bias exists in the ACOF predictions when applied to NSR shoes.

A regression model was created to determine whether the parameters (tread surface area, hardness, and heel shape) that predict ACOF for SR similarly predict ACOF for NSR shoes. The ACOF data for NSR shoes collected in this study was combined with the data previously collected and reported for SR shoes [74]. ACOF was the dependent variable and the independent variables included shoe type (NSR vs. SR), flooring, and the previously observed parameters for predicting friction, specifically tread surface area, hardness, heel shape. First-order interaction effects between the shoe type and each shoe parameter (tread surface area, hardness, and heel shape), and the interaction between shoe type and flooring were also included. After the full model was determined (Eq. 7), backward elimination step-wise regression was used to remove insignificant parameters from the model, based on the parameter with the largest p-value. These steps were repeated until no parameters in the final model had a p-value greater than 0.05. Shapiro-Wilk W test was applied to assess the distribution of continuous predictors. The distribution of residuals and homoscedasticity were assessed using residual plots. Linearity was also assessed for each regressor.

To test the contribution of fluid drainage to friction performance in NSR shoes, a regression model was applied to determine the effect of peak fluid pressure on the ACOF for NSR shoes. The model regressors included peak fluid pressure, flooring, and their interaction. ACOF was log-transformed to meet the linearity assumption consistent with other papers [24]. A square root transformation was applied to peak pressure to satisfy the normal distribution assumption, consistent with prior research [77]. This sample size was sufficient for capturing a fluid pressure effect with a Cohen's  $f^2 = 0.28$ , exceeding the sensitivity observed in prior studies ( $f^2 = 0.82$  based on Sundaram et al., [77]). The residuals of the model were assessed with a Shapiro-Wilk Test and residuals were assessed for homoscedasticity. Linearity was also assessed between fluid pressure and ACOF.

## **E.2.2.2.Results**

### **E.2.2.2.1.Descriptive Results**

The mean ACOF for NSR shoes was 0.119, with a standard deviation of 0.077. The median/mean for peak fluid pressure was 47 kPa/153 kPa, and the interquartile range was 16 to 295 kPa. Tread surface area had a mean of 8.45 cm<sup>2</sup>, with a standard deviation of 4.20 cm<sup>2</sup>. Hardness had a mean of 63 with a standard deviation of 11. Finally, 10 NSR shoes were classified as beveled, and 5 had a flat heel shape.

The mean ACOF for SR shoes was 0.394, with a standard deviation of 0.150. Tread surface area had a mean of 11.58 cm<sup>2</sup> with a standard deviation of 2.48 cm<sup>2</sup>. SR shoes had an average hardness of 55.42 with a standard deviation of 6.34. Finally, of the 58 SR shoes, 29 were classified as beveled and 29 were classified as flat.

### E.2.2.2.2. Does the previously developed ACOF model systematically over or underestimate ACOF in NSR shoes?

The ACOF model systematically overestimated ACOF values of NSR shoes. The median difference was found to differ from 0 ( $z=13.0$ ,  $p<0.001$ ). The median of the difference between the estimated and actual ACOF values was 0.19 with an interquartile range of 0.074 to 0.31. Thus, the magnitude to which this regression model overestimated ACOF for NSR shoes was substantial.

### E.2.2.2.3. Linear Regression Model Comparing NSR and SR Shoes

After backward stepwise regression was completed, the significant regressors on ACOF were found to be shoe type ( $p < 0.0001$ ,  $F_{1,140} = 379.8$ ), flooring ( $p < 0.001$ ,  $F_{1,140} = 155.8$ ), tread surface area ( $p < 0.001$ ,  $F_{1,140} = 23.4$ ), the interaction between shoe type and flooring ( $p < 0.001$ ,  $F_{1,140} = 65.5$ ), and the interaction between shoe type and tread surface area ( $p < 0.0001$ ,  $F_{1,140} = 62.9$ ). Tread surface area was normally distributed ( $W = 0.984$ ,  $p = 0.0858$ ). The final regression equation is given in Eq. 8 ( $F_{5,140} = 224.1$ ). When considering the full data set, the error was relatively low (root mean square error = 0.060), indicating that the regression model fit the data well. Given the significant interaction between the shoe type and tread surface area (Figure 13), we quantified the sensitivity of SR and NSR shoes to tread surface area. The change in ACOF from the 1<sup>st</sup> to 3<sup>rd</sup> quartile in tread surface area led to 0.100 increase in ACOF for SR shoes but a 0.025 reduction in ACOF for NSR shoes. A larger increase in ACOF was observed for the ceramic floor relative to the laminate floor for SR shoes compared with NSR shoes. Thus, the effects of tread surface area and flooring did not generalize across SR and NSR shoes.

Full Model:

$$\begin{aligned}
 ACOF = & \beta_0 - \beta_{Shoe\ Type} * Shoe\ Type[NSR] + \beta_{Heel\ Shape} * Heel\ Shape[Beveled] + \\
 & \beta_{Tread\ Surface\ Area} * [Tread\ Surface\ Area] - \beta_{Hardness} * [Hardness] + \beta_{Flooring} * \\
 & [Ceramic] - \beta_{Shoe\ Type, Heel\ Shape} * [Beveled, NSR\ OR\ Flat, SR] - \beta_{Shoe\ Type, Tread\ Surface\ Area} * \\
 & (Shoe\ Type[NSR] * [Tread\ Surface\ Area]) + \beta_{Shoe\ Type, Hardness} * (Shoe\ Type[NSR] * \\
 & [Hardness]) + \beta_{Shoe\ Type, Flooring} * (Ceramic, NSR\ OR\ laminate, SR)
 \end{aligned}
 \tag{Eq. 7}$$

Backward Elimination:

$$\begin{aligned}
 ACOF = & 0.107 + 0.032 * Shoe\ Type[NSR] + 0.154[Ceramic] + \\
 & 0.0225[Tread\ Surface\ Area] - 0.028([Tread\ Surface\ Area] * Shoe\ Type[NSR]) - \\
 & 0.0998[NSR, ceramic\ OR\ SR, laminate]
 \end{aligned}
 \tag{Eq. 8}$$

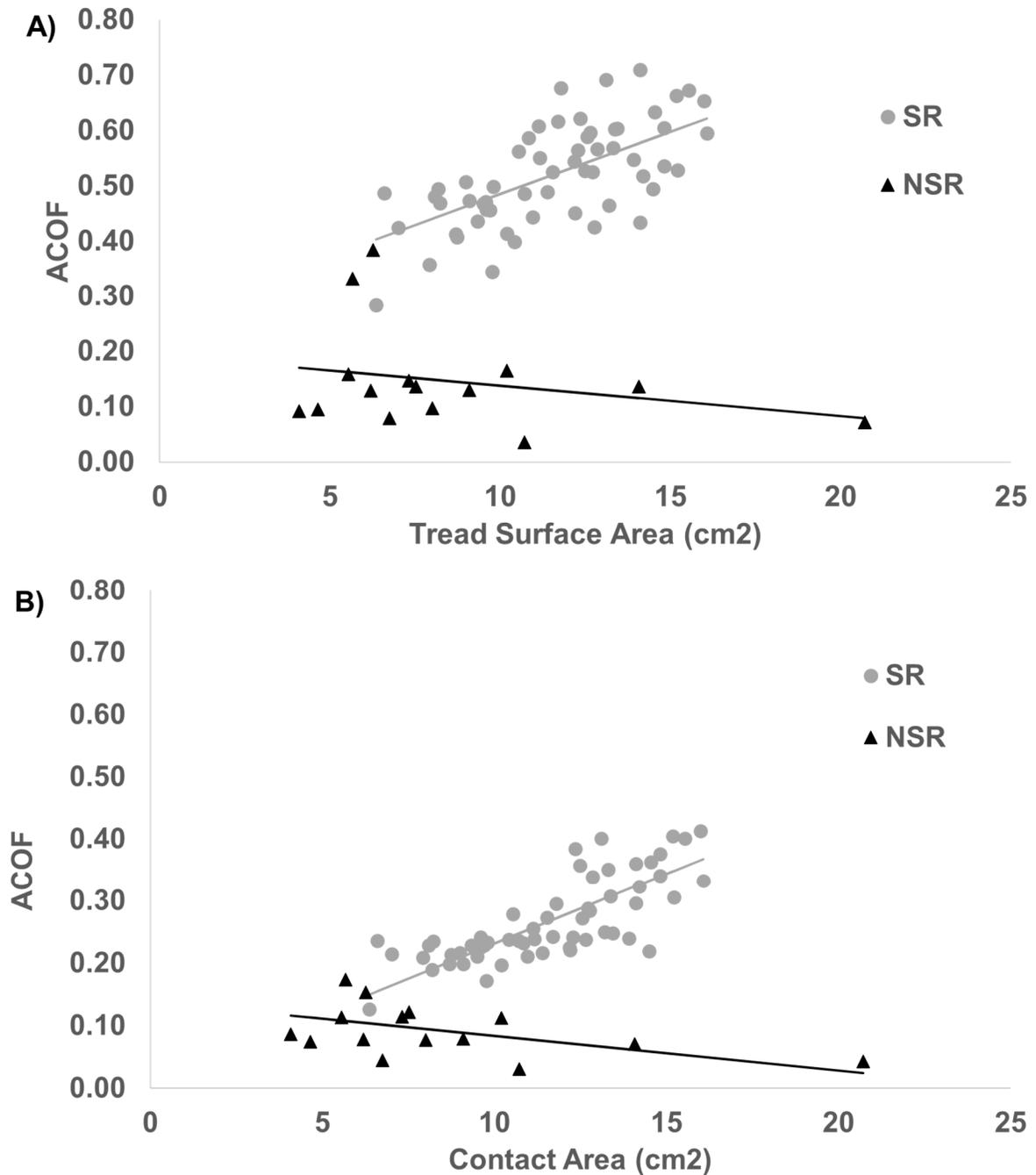


Figure 13. Response of ACOF to tread surface area for SR (SR, gray circles) and NSR (NSR, black triangle) shoes on ceramic (A) and laminate (B) flooring. The different slope for these two parameters is characterized by the different slope of the SR regression line (gray) from the NSR regression line (black).

#### E.2.2.2.4. Linear Regression Model of Peak Fluid Pressure on ACOF

Flooring ( $p = 0.012$ ,  $F_{1,27} = 7.3$ ) and peak fluid pressure ( $p < 0.001$ ,  $F_{1,27} = 20.8$ ) influenced ACOF for NSR shoes, but not their interaction ( $p = 0.85$ ,  $F_{1,26} = 0.0$ ). Thus, the step-wise method led to

the removal of the interaction effect from the final model (Eq. 9) The residuals were normally distributed ( $W = 0.940$ ,  $p = 0.0885$ ). Increased fluid pressures were associated with a reduction in ACOF (Figure 14, Eq. 9). The coefficient of determination ( $R^2$ ) was 0.51, and the RMS error was 0.064. A 47% decrease in ACOF (0.080 for ceramic and 0.053 for laminate) is predicted as fluid pressure increased from the 1<sup>st</sup> to 3<sup>rd</sup> quartile of NSR shoes.

$$ACOF = 0.136 * 1.50[Ceramic]e^{-0.0484*\sqrt{PeakFluidPressure}} \quad \text{Eq. 9}$$

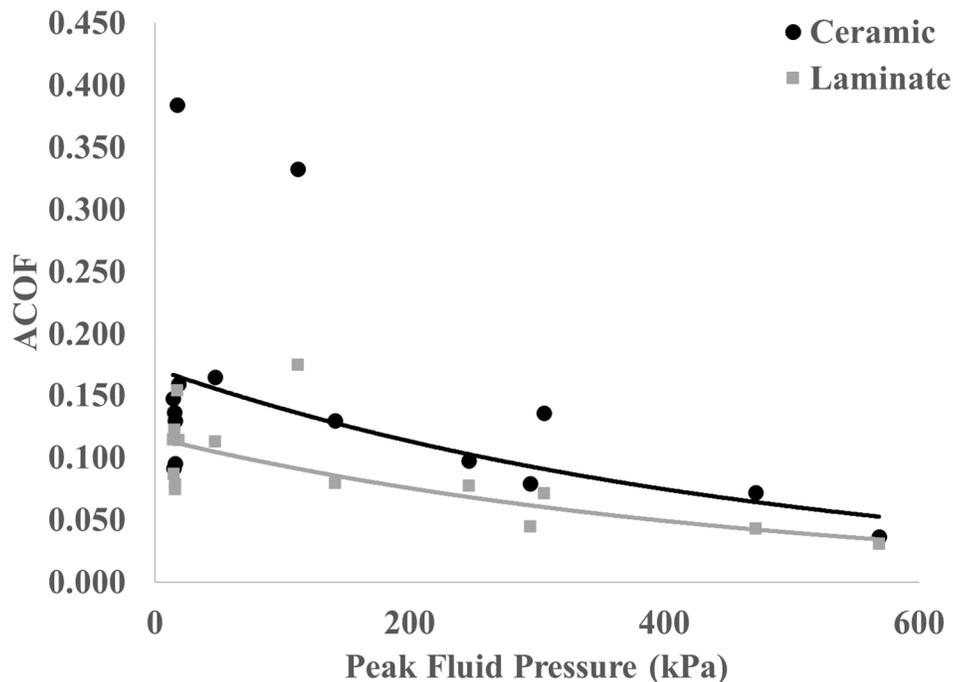


Figure 14. Linear Regression model of ACOF predicted by the peak fluid pressure and flooring. The fit lines are not linear due to the transformations ( $\ln(ACOF)$ ,  $\sqrt{Peak Fluid Pressure}$ ) that were performed. The overall regression equation is seen in Eq. (9).

### E.2.2.3. Discussion

This study provided clear evidence that regression equations developed for SR shoes based on the assumption of boundary lubrication cannot be applied to NSR shoes. This finding conflicts with the first hypothesis. These models overestimate friction by a large magnitude compared to the observed friction values and the interaction between shoe type and tread surface area indicates that tread surface area has an opposite effect on SR and NSR shoes. The linear regression model showed that the peak fluid pressure and flooring significantly predicted the ACOF for NSR shoes. Thus, the hydrodynamic pressures seem to explain the variability across NSR shoes, while tread design parameters that influence boundary lubrication, as described in Iraqi et al. [74], seemed to explain the variability for SR shoes. Increasing peak fluid pressure from the 1<sup>st</sup> to 3<sup>rd</sup> quartile led to a nearly 50% reduction in ACOF, which indicates that the impact of fluid pressure on NSR shoes was substantial. The first hypothesis that the ACOF of NSR shoes responded similarly to shoe design parameters as SR

shoes was rejected. The second hypothesis that the ACOF of NSR shoes was dependent on under-shoe fluid pressures was confirmed.

The high fluid pressures that were observed for NSR shoes indicate that the tread channels were insufficient for fluid drainage. This result is consistent with previous research that showed higher fluid pressures for worn NSR shoes compared to worn SR shoes [77]. The negative slope that was observed between ACOF and fluid pressure is consistent with previous research, which suggests that the separation of the floor and shoe due to a fluid contaminant pressurization reduces the ACOF substantially [10]. Thus, this research adds to the growing body of evidence that under-shoe fluid pressurization is a relevant factor for shoe friction performance and the risk of slipping. Finally, the poor friction performance associated with popular shoes (Figure 13) is consistent with finding based on icy friction performance [81, 82].

Clearly, the impact of tread surface area and flooring on ACOF for NSR shoes was inconsistent with previous research that measured its impact on ACOF for SR shoes [40, 74]. One explanation for this discrepancy is that different mechanisms were dominating the variability in friction between these two shoe types. Boundary lubrication, which has been shown to apply to SR shoes, describes the condition in which the liquid film between the shoe and floor is not pressurized [83]. For SR shoes, boundary lubrication is promoted by tread channels that provide a low-resistance means for the fluid to escape from the under-shoe interface [32, 79]. However, based on the results of the collected fluid pressure values in this study, the tread pattern of NSR shoes does not allow for the fluid to drain causing the shoe to operate in mixed or hydrodynamic lubrication. This finding may explain why increasing tread surface area for NSR shoes without increasing channels for fluid escape results in a decrease in ACOF. The larger continuous contact regions of the NSR shoes may have mimicked worn regions [84], which lead to a reduction in ACOF as their size (and surface area) increases [77, 85, 86]. Interestingly, the flooring had a larger effect on ACOF for SR shoes than NSR shoes consistent with prior research [87]. Floor roughness has a large impact on hysteresis friction when the shoe is operating in boundary lubrication [42, 64]. Thus, SR shoes operating in boundary lubrication, may be able to realize the benefits of high roughness flooring more than NSR shoes that are operating in mixed lubrication.

The key finding is that the set of diagnostic methods used to improve friction for SR shoes do not apply to NSR shoes. Thus, a different set of tools is needed that focuses on reducing fluid pressures such that shoes operate closer to boundary lubrication. One possibility would be to test whether NSR shoe treads can be modeled using a tapered wedge model that was recently validated for worn SR shoes [79]. Other factors beyond tread drainage may also be relevant like the surface energy of the shoe materials and their porosity [88]. Thus, further research is needed to develop dedicated prediction models for NSR shoes.

Certain limitations pertaining to generalizability and this study's methodology should be acknowledged. As this testing only included fifteen NSR shoes, the regression model connecting fluid pressures to ACOF may not have been trained with sufficient data to be precise. While the 15 selected shoes represent some of the most popular shoe products at the time of purchase, they only represent a small fraction of the overall shoe products available. Improved friction performance may be observed in certain categories of NSR shoes (e.g., hiking boots).

This paper has shown that the model to predict ACOF for SR shoes cannot be applied to NSR shoes. As a result of these differences, tread surface area has an opposite effect for the two shoe types, and the effect of flooring on ACOF is smaller for NSR shoes. Furthermore, this study has shown that there is at least one extra parameter, peak fluid pressure, that needs to be accounted for in a prediction model for ACOF of NSR shoes. This indicates that designers of NSR shoes should prioritize tread drainage channels when attempting to improve the friction performance of their shoes.

### **E.2.3. Aim #1, Study #3: Extending the model to non-oily conditions (sodium laurel sulfate) [confidential]**

#### **E.2.3.1. Methods**

A total of 55 slip-resistant shoes were tested in the presence of diluted sodium laurel sulfate (SLS) at a concentration of 0.5% SLS and 99.5% water. The shoes and testing conditions were consistent with the shoes described in the data set for Study #1 (E.2.1.) with the exclusion of 3 shoes that were unable to meet the force requirements for a good test (shoe codes from Table 1: F3, E6, and E8). One flooring condition, laminate consistent with one of the floor designs utilized in Study #1, was tested. All data analysis methods for calculating ACOF and tread parameters was consistent with the methods described in Study #1. This study analyzed these 55 shoes in SLS conditions and the 58 shoes in oily conditions presented in Study #1.

Two analyses were performed: first a bivariate regression to determine whether the oily ACOF values were correlated with the SLS-contaminated conditions. Second, a stepwise regression model with forward selection was utilized with regressors entering the model in order of the lowest p-value with a requirement of  $p < 0.05$  to enter the model. The independent variables were the same as those considered in Study #1 with two differences: the contaminant condition was included as a dichotomous nominal variable along with its interaction effect with the shoe tread parameters; and flooring along with its interaction effects was not included in the model since only one floor condition was considered.

#### **E.2.3.2. Results**

The mean (standard deviation) for oily and SLS-contaminated COF were 0.267 (0.066) and 0.423 (0.080), respectively. A shoe's oily COF conditions were weakly, but significantly correlated with the SLS condition ( $t_{53} = 3.45$ ,  $p = 0.001$ ,  $R^2 = 0.183$ ) (Figure 15). The forward selection model yielded the following regressors ( $R^2 = 0.740$ ) (Figure 16): heel shape, contact area, shape factor, hardness, contaminant condition, the interaction effect between contact area and hardness, and an interaction effect between hardness and contaminant. Some of the effects were consistent with the oily model (Study #1) including: higher ACOF associated with a beveled shape, increased contact area, and lower hardness, Eq. (10). An increased shape factor (more rigid geometry) was associated with lower ACOF values. Increased contact area and lower hardness had a synergistic effect. The effect of hardness on ACOF was greater for the SLS condition than the oily condition. The RMS error for oily conditions was 0.040 and the RMS error for SLS conditions was 0.066).

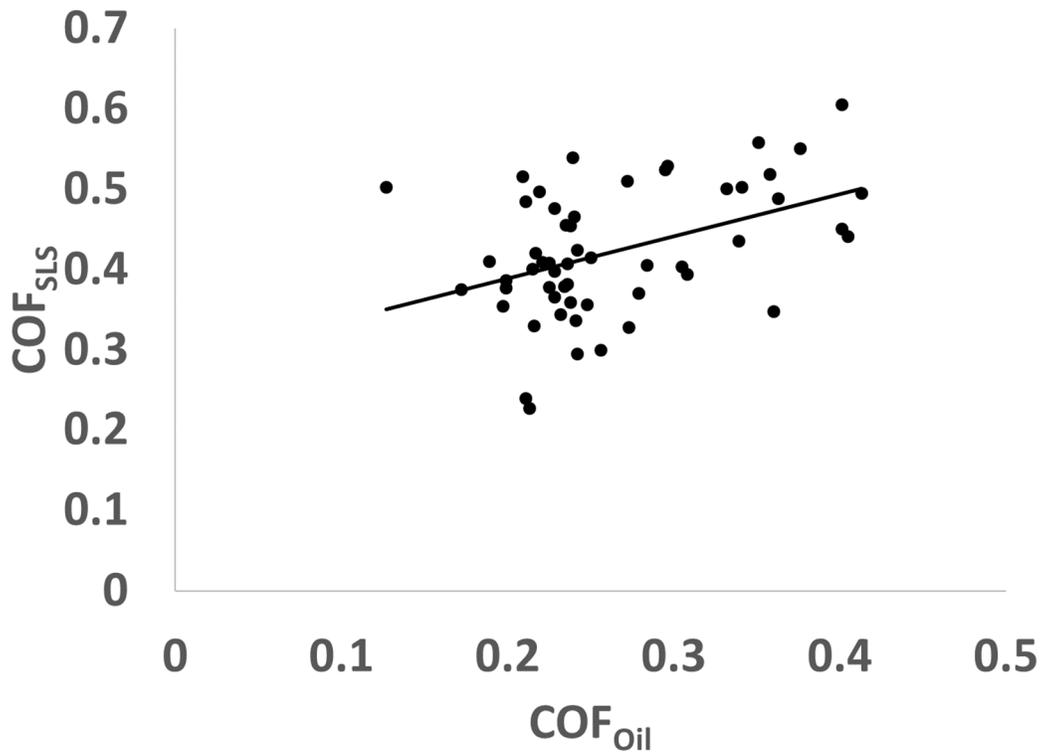


Figure 15: Correlation between COF measured in the presence of SLS relative to the COF measured in the presence of oil.

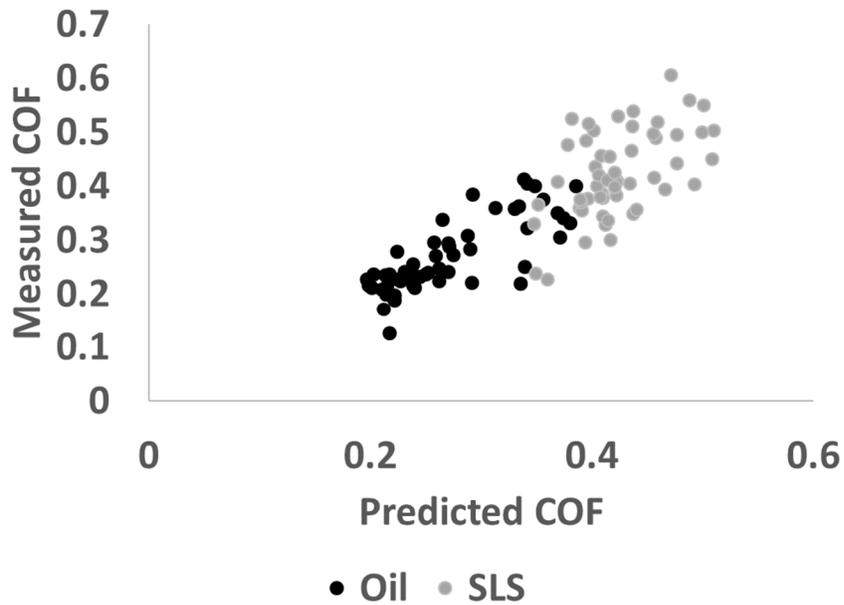


Figure 16: Plot of the measured COF relative to the COF predicted by the regression equation (Eq. (10))

$$ACOF = 0.332 + 0.026 * Heel\ Shape[Bevel] + 0.012 * Contact\ Area\ [cm^2] - 0.096 * Shape\ Factor - 0.0033 * Hardness[Shore\ A] + 0.157 * Contaminant\ [SLS] - 0.0019 * (Contact\ Area[cm^2] - 11.5) * (Hardness[Shore\ A] - 55.4) + 0.0041 * Contaminant\ [SLS] * (Hardness[Shore\ A] - 55.4) \text{ Eq. (10)}$$

### E.2.3.3. Discussion

The relatively low correlation between the oily conditions and the SLS conditions suggest that the oily condition did not capture the salient mechanics present in the SLS condition. Furthermore, the complex and difficult to interpret interaction effects that were observed both across tread parameters and between tread and contaminant variables suggest increased complexity in attempting to predict friction in the presence of non-oily contaminants. Furthermore, the RMS error was substantially larger for SLS conditions compared to oily conditions. Thus, it is unclear whether adhesion friction can be adequately predicted with the same outsole parameters.

This study suggests that the parameters that predict friction in the presence of hysteresis friction (relevant to oily conditions) do not necessarily extend when adhesion is present (relevant to SLS conditions). Notably, the selection of outsole parameters was based on expectations around hysteresis friction from theory and from models [40, 44, 74]. Thus, it is not entirely unexpected that it did not apply quite as well to conditions where adhesion friction was present. Other parameters that might be relevant for adhesion friction would be the surface energy properties and topography of the shoe and floor surface [10, 42, 64, 72]. Unfortunately, these measures require specialized equipment and specially trained researchers that may make them inaccessible to most ergonomists. Moving forward, more specialized knowledge and models of shoe-floor adhesion may be needed to inform simple guidelines for enhancing this form of friction.

While this study was not able to extend the regression models to adhesion friction in a simple and straight-forward way, the results can still inform footwear safety for non-oily conditions. For 57 of the 58 shoes that were considered, ACOF was higher for SLS than it was for oily conditions. For the one shoe where this was not the case, the ACOF was only slightly less (0.011) for SLS than oil. This suggests that shoes that have a safe level of ACOF in oily conditions also will be safe in SLS conditions. Note that the opposite conclusion cannot be made. One of the shoes that was among the top quartile for ACOF in the presence of SLS (D7, ACOF = 0.503), had the lowest ACOF in oily conditions (ACOF = 0.127). In the presence of non-oily conditions, the total ACOF is the sum of the hysteresis friction (captured during oily tests) and a portion of the adhesion friction (ref). Thus, empirical and theoretical evidence support the concept that using oily ACOF values can identify footwear that is safe across SLS contaminant conditions. While this study only considered SLS contaminant, we would expect the results may be applicable to other conditions where adhesion is present (such as wet conditions).

This study has some limitations that should be acknowledged. First, only a single flooring surface was considered. Because adhesion effects are influenced by the coupled surface energy of shoes and flooring [72, 89], we might expect that these models may be influenced by the floor surface. Second, we likely would not expect the results of this study to apply to non-slip-resistant shoes, especially considering the observations from Study #2. Lastly, we did not perform cross-validation analyses in the development of our model, which may have led to some overfitting. While this study may identify tread patterns that influence friction performance, the validity of the actual regression equations have not been fully characterized.

In conclusion, this study suggests that different mechanical phenomena contribute to friction in non-oily conditions and that the tread parameters, which predict friction in oily conditions do not similarly apply to non-oily conditions. However, shoes that demonstrate safe friction performance in oily conditions typically also have safe friction performance in non-oily conditions. Thus, shoe prediction models for oily conditions may yield generalizable safety information about the shoes even if they do not predict the exact friction performance for all conditions.

#### **E.2.4. Aim #2, Study #4: Predicting human slips based on tread outsole parameters of slip-resistant shoes [confidential]**

The purpose of this study was to assess the predictive ability of the model from Iraqi et al. [74] to predict human slips. Importantly, this study uses materials that deviate from those used to train the model in terms of shoe models and the floor surface. This study also considers a variety of shoe sizes whereas the original study only considered a single shoe size.

##### **E.2.4.1. Methods**

A total of 38 participants were included in this data collection. These participants were pooled across two studies with identical data collection methods: one that aimed to validate the predictive ability of a portable tribometer ( $n = 18$ ), which was supplemented with new data to achieve the goals of the present study ( $n = 20$ ). From the prior study, only participants that were exposed to oil on a porcelain tile floor surface were included in this analysis. Another 8 participants ( $n = 4$  from prior study and  $n = 4$  from this analysis) were excluded due to the participant being aware of the fluid contaminant prior to stepping on it ( $n = 3$ ), the shoe being unavailable for testing after data collection ( $n = 2$ ), data collection errors ( $n = 2$ ), the participant not stepping in the contaminant ( $n = 1$ ). Prior to data collection, a database of footwear was curated that included 26 different brands. Participants were randomly matched with footwear, ensuring that they received footwear consistent with their reported gender and shoe size. In some cases, footwear models were replaced with a new year's models. When this happened, a shoe in the database was replaced with a similar shoe from the new year's models by the research team.

Participants donned the slip-resistant shoes, a safety harness, and a set of 79 markers. One marker on the inferior-most point of the shoe heel was used to assess slipping outcome (see subsequent paragraph on data analysis for details). Participants completed a series of baseline (dry) walking trials on the tile surface, while the required coefficient of friction was captured from a force plate. After about 10 dry trials were completed, canola oil was placed on a floor tile without the awareness of the participant. The participant completed a single trial where they walked on the oily surface.

Two biomechanical variables were extracted from the human participant data: slip outcome and RCOF. Slip outcome was calculated based on the displacement between slip onset and the end of a slip [24, 40, 90]. Slip onset was determined as the local minimum in slipping speed prior to the peak slipping speed but after foot contact. Slip completion was the local minimum in slipping speed after peak slipping speed. A slip distance exceeding 3 cm was considered a slip. The RCOF was based on the highest local maximum for the ratio of friction to normal force when the following conditions were met [68, 91]: minimum normal force of 100 N, force applied to the floor by the shoe was in the anterior direction, and within 200 ms of foot contact.

COF values were predicted based on the tread outsole features and were not directly measured. The COF prediction model includes three tread parameters: tread surface area, heel beveling, and shoe hardness. These tread parameters were each measured by a single evaluator to reduce variability across evaluators from influencing the results. Tread surface area and shoe hardness were collected using identical methods to Iraqi et al. [74]. Briefly, tread surface area was measured by coating the tread with ink, making an imprint while pressing down on the insole to, scanning the imprint, and then summing the contact area in the posterior 50 mm region. Hardness was measured by placing the shoe in a vice and applying a Shore A durometer (with a 1 kg mass to improve consistency). The method to assess shoe beveling was modified to enhance objectivity in the measure. The shoe bevel was assessed based on whether the back of the heel reached a certain distance off of the floor surface when no external forces were applied. Specifically, the posterior 5 mm of the shoes had to be more than 4 mm off of the ground. This was assessed by lining up the back of the heel with the edge of a table surface, while ensuring that a USB-A port (from the edge to the latch opening) could fit under the heel surface (Fig. 17). COF was predicted using Eq. 11 where the parameters in brackets were the

units in the case of tread surface area hardness. Shoes with a bevel were assigned a dummy variable (*heel shape*) of 1, while shoes without a bevel were assigned a 0. The floor surface variable was removed from this prediction model since the flooring used in this study was different from the two floor surfaces used to train the data set.



Figure 17: Demonstration of the test used to assess whether shoes contained a bevel. A USB port was placed beneath the heel and the shoe was considered to have a bevel if there was enough space to accommodate the USB port. Note that the back of the outsole was aligned over the latch ports (rectangular holes) of the USB port.

$$COF_{Predicted} = 0.223 + 0.015 * \text{tread surface area} \\ [\text{cm}^2] + 0.041 * \text{heel shape}[\text{bevel}] - 0.003 * \text{hardness} [\text{Shore A}] \quad \text{Eq. (11)}$$

A univariate and multivariate logistical regression models were used to assess whether the COF prediction model was associated with slips. In the univariate model, slip outcome was the dependent variable and predicted COF was the independent variable. In the multivariate model, RCOF was also added as an independent variable. The area under the receiver operating characteristic curve were reported.

#### E.2.4.2. Results

The mean (standard deviation) of the predicted COF values were 0.235 (0.060) based on a mean (standard deviation) of 10.7 cm<sup>2</sup> (3.3 cm<sup>2</sup>) for tread surface area and 59.1 (7.1) for hardness. Of the 38 participants and shoes, 14 experienced slips (37%) and 26 (68%) included a bevel, respectively. The mean (standard deviation) of RCOF was 0.198 (0.040).

Shoes with a larger predicted COF value were associated with a reduction in slip outcome for both the univariate and multivariate statistical models (Table 5). The univariate model yielded significant predictions for the predicted COF ( $p=0.010$ ,  $\chi^2_{(1)} = 6.6$ ) (Figure 18). The odds ratio across the

interquartile range of predicted COF (COF increase of 0.075) was 0.291 (95% confidence interval: 0.101 to 0.842). The area under the receiver operating characteristic curve was 0.711. The multivariate model also yielded significant contribution of the predicted COF to slipping ( $p=0.008$ ,  $\chi^2_{(1)} = 7.1$ ) but did not yield a significant result for RCOF ( $p=0.190$ ,  $\chi^2_{(1)} = 1.7$ ).

Table 5: Results of the univariate and multivariate models. No p-value is provided for the intercept since this hypothesis testing was not conducted. AUC refers to the area under the receiver operating characteristic curve. The  $\beta$  values refer to the coefficients in the regression equations provided in the footnotes.

Statistical Model	Independent Variable	$\beta$	p-value	AUC
Univariate	Intercept	-3.2†	*	0.711
	COF <sub>Predicted</sub>	14.9†	0.010	
Multivariate	Intercept	-1.2‡	*	0.729
	COF <sub>Predicted</sub>	17.8‡	0.008	
	RCOF	-12‡	0.19	

\* Significance was not determined for the intercept variable.

$$\dagger P(\text{slip}) = \frac{1}{1 + e^{\beta_{\text{Intercept}} + \beta_{\text{COF}_{\text{Predicted}}} * \text{COF}_{\text{Predicted}}}}$$

$$\ddagger P(\text{slip}) = \frac{1}{1 + e^{\beta_{\text{Intercept}} + \beta_{\text{COF}_{\text{Predicted}}} * \text{COF}_{\text{Predicted}} + \beta_{\text{RCOF}} * \text{RCOF}}}$$

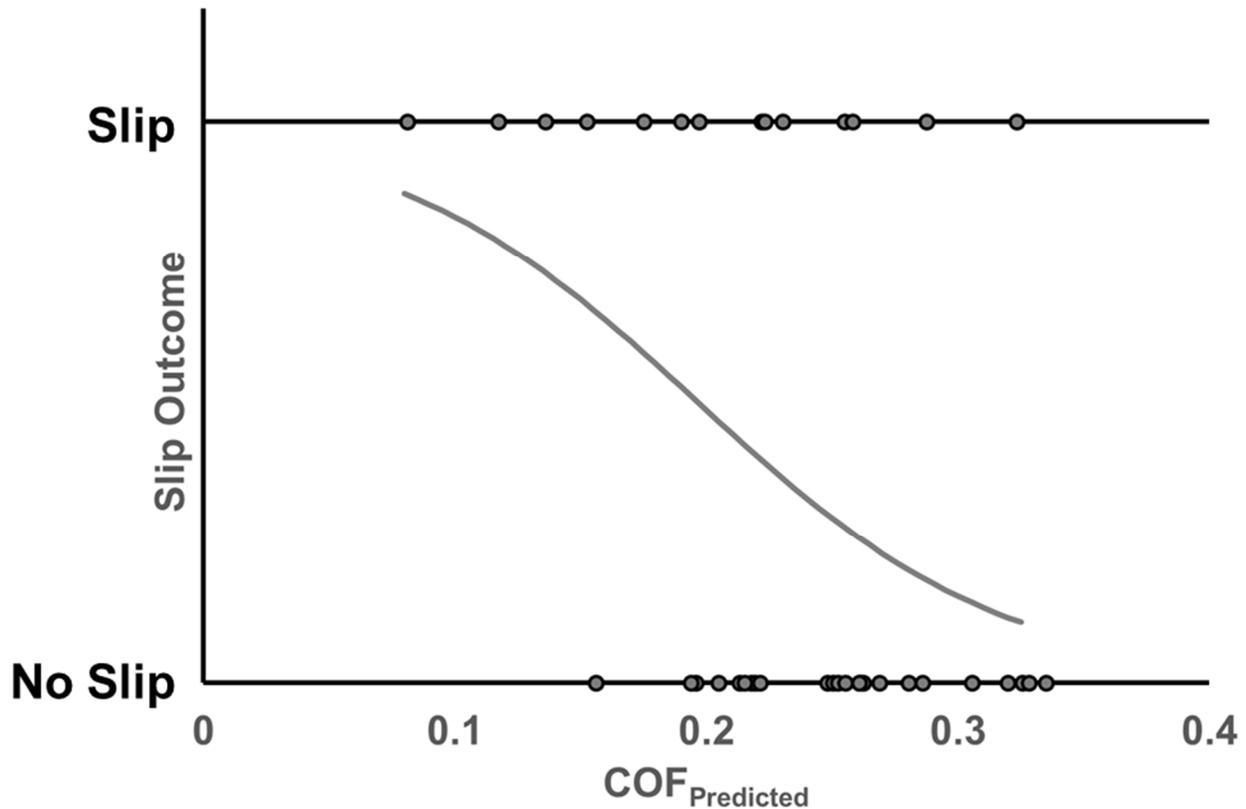


Figure 18: The logistic regression plot for the univariate analysis where slip outcome is fit by the predicted COF values from the model. Each point represents the outcome from an individual participant, while the line represents the fit line.

### **E.2.4.3. Discussion**

This study demonstrated that slipping risk is predictable based on shoe design. This study adds to a growing body of evidence that slipping risk for slip-resistant shoes is dependent on hysteresis friction and the tread features that target this mechanism. As such, there is substantial incentive to ensure that slip-resistant shoes achieve good hysteresis friction by enhancing surface area, reducing hardness, and incorporating a heel bevel.

This study extends the results of our prior study that demonstrated that these three tread features were associated with increased friction [74]. Performing replication studies using different methods is an advisable way to demonstrate the robustness of research results [92]. This study deviated from the prior study by using different shoes, a different floor surface, and a different outcome measure (slip outcome instead of COF). The consistent results under varied experimental conditions indicate robustness in the results relating outsole features to friction performance and slip risk. Other studies have similarly found that a reduction in contact area due to tread bending is associated with a loss in friction [93], that the pressure dependence of elastomers can be modeled with finite element analysis [44]. The Payne effect, which indicates that the material properties of filled rubbers are strain dependent [94], may explain the pressure-dependence of shoe-floor friction, since higher pressures would result in higher strains. Therefore, a theoretical basis also exists for the observed trends further supporting the validity of this model.

This study provides justification for footwear manufacturers and consumers to alter their behavior around designing and selecting footwear. When possible, footwear designers could try to alter their designs to enhance the three design features that are part of the shoe predictive model. However, we should note that there are important tradeoffs when altering tread surface area and hardness. Tread surface area can only be increased so much before encroaching the tread channels or going outside of the shoe form. Reducing tread channels may at some point increase in hydrodynamic pressures offsetting the benefit of reduced contact pressures. Going outside of the shoe form may potentially increase trip risk. Altering the hardness may have similar unintended consequences including altering the viscoelastic properties needed for hysteresis friction or the material durability. In contrast to surface area and hardness, it is difficult to identify potential consequences for adding shoe beveling. Thus, the 32% of shoes that did not include a bevel may be missing a critical feature. This may be an important feature to guide both footwear manufacturers and footwear consumers.

Like all studies, this study has limitations that should be considered. The hysteresis friction mechanism, that is believed to be most relevant to the statistical model, is only applicable to oily surfaces in the absence of hydrodynamic lubrication. Notably, prior studies have found that this model only applies to slip-resistant shoes that operate in boundary lubrication [95] (Section E.2.2.). It is unclear how this model would apply in lower viscosity conditions like water, where adhesion is more prominent. Furthermore, the reliability of the tread assessments still needs to be characterized before this test is ready to be deployed on a large scale. Lastly, the regression models should not be extrapolated beyond the range of variables that have been considered in experiments.

In conclusion, this study demonstrated that a friction-prediction model based on tread outsole features can yield valid predictions of slipping. This study provides further evidence that design features predictably influence slip risk and suggests that these can be modified to manage risk. The implementation of this knowledge is expected to reduce the burden of slip and fall injuries.

### **E.3. Barriers and obstacles impeding progress**

Consistent with most research projects, unexpected challenges occurred that impeded progress towards the originally planned aims and hypotheses. In addition, certain observations led us to alter our research approach in future experiments. Despite these barriers and obstacles, our research team believes that a substantial amount of progress was made for each aim consistent with the intent of our original proposal.

### E.3.1. More tests under oily conditions, fewer tests under wet conditions, and fluid pressures only measured for some conditions

We modified the testing conditions for Aim 1 in response to new scientific evidence suggesting that shoe tread parameters were better associated with oily friction than other forms of friction. After we developed the research proposal but before we started conducting tests, research emerged that demonstrated that tread parameters that influenced contact pressure influenced hysteresis friction, which is dominant during oily friction but not dominant during other forms of friction [40, 44]. Furthermore, friction during oily friction was poorly to moderately correlated with friction performance for other contaminants (water, diluted sodium laurel sulfate) [73, 78] indicating that hysteresis was only a portion of the overall friction and that adhesion friction was substantive. Adhesion friction has been recently found to be associated with surface energy and spreading coefficients [96], which may indicate that the features targeted in this study were unlikely to predict friction in wet, non-oily conditions. Thus, the number of conditions for oily surfaces were increased (78 shoes) to compensate from the reduced number of wet conditions.

### E.3.2. Fewer participants, pooled data, and only a single slip

We deviated from our plan to test 30 participants and to complete 2 slips per participant. We had anticipated to collect participant data in the spring and summer of 2020 consistent with our proposed timeline. Unfortunately, the pandemic restricted our ability to collect this data and we collected this data under restrictions and a compressed timetable in 2021. Furthermore, we only completed one slip per participant based on reviewer feedback for our other publications that included two slips per participant [24, 40, 90]. To compensate for fewer number of slips in our data set, we pooled the new data with data from another study that used identical procedures and had a data subset that was applicable to the aims of this study. Furthermore, our statistical models demonstrated more predictive ability than we had initially planned, which enabled us to utilize less data. Thus, we were able to answer the research questions posed in Aim 2 with fewer number of slips.

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## **F.Publications**

### **F.1. Journal Article:**

1. Meehan, E, Vidic, N, Beschorner, KE: [2022] In contrast to slip-resistant shoes, fluid drainage capacity explains the variable friction performance in shoes that are not marketed as slip-resistant, *Applied Ergonomics*, **in review**.
2. Iraqi, A, Vidic, NS, Redfern, MS and Beschorner, KE: [2020]. Prediction of coefficient of friction based on footwear outsole features. *Applied Ergonomics*, **82**, p.102963. Pubmed ID: PMC31580996.

### **F.2. Proceedings:**

1. Beschorner, KE, Meehan, EE, Iraqi, A, Hemler, SL: [2021] Designing Shoe Tread for Friction Performance: A Hierarchical Approach, *Footwear Biomechanics Symposium, Virtual Conference*, 597-599, *Footwear Science* **13**, July 21-23, 2021.
2. Iraqi, A., Beschorner, K.E., 2019, Effect of Shoe Outsole Backing on the Coefficient of Friction, *Society of Tribologists and Lubrication Engineers Annual Meeting, Nashville, TN, May 19-23, 2021*.
3. Beschorner, K.E., Hemler, S.L., Moghaddam, S.R., Iraqi, A., Moyer, B.E., Haight, J.M., Redfern, M.S., 2018, Preventing slip and fall accidents: Focus on footwear, *National Occupational Injury Research Symposium, Morgantown, WV, October 16-18, 2021*.

### **F.3. Dissertation/Thesis**

1. Iraqi, A: [2018] Predictive Statistical Models for Shoe-Floor-Contaminant Friction, Ph.D. Thesis, University of Pittsburgh.

## G. Inclusion Enrollment Table

View Burden Statement

**PHS Inclusion Enrollment Report**

This report format should NOT be used for collecting data from study participants.

OMB Number: 0925-0001 and 0925-0002  
Expiration Date: 10/31/2018

\*Study Title (must be unique): Reducing slip-and-fall accidents in the workplace: Role of small-scale roughness of floor surfaces to improve friction

\* Delayed Onset Study?  Yes  No

*If study is not delayed onset, the following selections are required:*

Enrollment Type  Planned  Cumulative (Actual)

Using an Existing Dataset or Resource  Yes  No

Enrollment Location  Domestic  Foreign

Clinical Trial  Yes  No

NIH-Defined Phase III Clinical Trial  Yes  No

Comments:

Racial Categories	Ethnic Categories									Total
	Not Hispanic or Latino			Hispanic or Latino			Unknown/Not Reported Ethnicity			
	Female	Male	Unknown/ Not Reported	Female	Male	Unknown/ Not Reported	Female	Male	Unknown/ Not Reported	
American Indian/ Alaska Native	0	0	0	0	0	0	0	0	0	0
Asian	1	3	0	0	0	0	0	2	0	6
Native Hawaiian or Other Pacific Islander	0	0	0	0	0	0	0	0	0	0
Black or African American	1	0	0	0	0	0	0	0	0	1
White	7	6	0	0	0	0	1	0	0	14
More than One Race	2	2	0	0	0	0	0	0	0	4
Unknown or Not Reported	0	0	0	0	0	0	0	0	0	0
<b>Total</b>	<b>11</b>	<b>11</b>	<b>0</b>	<b>0</b>	<b>0</b>	<b>0</b>	<b>1</b>	<b>2</b>	<b>0</b>	<b>25</b>

Report 1 of 1

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Table 6: Both minorities and women were included in the study

## H. Inclusion of Children

Children under 21 years of age were eligible and participated in this study. This study is similarly applicable to children of the ages 18 to 21 years since they participate in the workforce and are similarly at risk of slipping. We expect that the results of the study are similarly applicable to this segment of children and adults.

## I. Materials Available for Other Investigators

We are currently in the process of making material available for other investigators. One data set has already been made available as a supplemental document to our publication (Iraqi et al., 2020) and another dataset will be made available for Aim 2. Spreadsheet file format will be used for wide accessibility of the data (.csv). Data files will be accompanied with a document that explains the data structure and provides descriptions for each column.

**C. PRODUCTS**

**C.1 PUBLICATIONS**

Are there publications or manuscripts accepted for publication in a journal or other publication (e.g., book, one-time publication, monograph) during the reporting period resulting directly from this award?

Yes

**Publications Reported for this Reporting Period**

Public Access Compliance	Citation
N/A: Not NIH Funded	Iraqi A, Vidic NS, Redfern MS, Beschorner KE. Prediction of coefficient of friction based on footwear outsole features. Applied ergonomics. 2020 January;82:102963. PubMed PMID: 31580996; PubMed Central PMCID: PMC7365588; DOI: 10.1016/j.apergo.2019.102963.

**C.2 WEBSITE(S) OR OTHER INTERNET SITE(S)**

NOTHING TO REPORT

**C.3 TECHNOLOGIES OR TECHNIQUES**

Category	Explanation
Evaluation Instruments	We developed and validated a new evaluation instrument that can predict shoe-floor-oily friction based on tread surface area, shoe hardness, presence of a heel bevel, and the floor surface. This regression equation is presented in the following reference Iraqi A, Vidic NS, Redfern MS, Beschorner KE. Prediction of coefficient of friction based on footwear outsole features. Applied ergonomics. 2020 January;82:102963. PubMed PMID: 31580996; PubMed Central PMCID: PMC7365588; DOI: 10.1016/j.apergo.2019.102963.

**C.4 INVENTIONS, PATENT APPLICATIONS, AND/OR LICENSES**

Have inventions, patent applications and/or licenses resulted from the award during the reporting period? No

If yes, has this information been previously provided to the PHS or to the official responsible for patent matters at the grantee organization?

**C.5 OTHER PRODUCTS AND RESOURCE SHARING**

Category	Explanation
Data or Databases	As part of the supplemental material, we provided our shoe-floor-COF database to accompany our publication: Iraqi A, Vidic NS, Redfern MS, Beschorner KE. Prediction of coefficient of friction based on footwear outsole features. Applied ergonomics. 2020 January;82:102963. PubMed PMID: 31580996; PubMed Central PMCID: PMC7365588; DOI: 10.1016/j.apergo.2019.102963.



## D. PARTICIPANTS

### D.1 WHAT INDIVIDUALS HAVE WORKED ON THE PROJECT?

Commons ID	S/K	Name	Degree(s)	Role	Cal	Aca	Sum	Foreign Org	Country	SS
BESCHORNER	Y	Beschorner, Kurt E	BS,PHD	PD/PI	1.0	0.0	0.0			NA

#### Glossary of acronyms:

S/K - Senior/Key

DOB - Date of Birth

Cal - Person Months (Calendar)

Aca - Person Months (Academic)

Sum - Person Months (Summer)

Foreign Org - Foreign Organization Affiliation

SS - Supplement Support

RE - Reentry Supplement

DI - Diversity Supplement

OT - Other

NA - Not Applicable

### D.2 PERSONNEL UPDATES

#### D.2.a Level of Effort

Not Applicable

#### D.2.b New Senior/Key Personnel

Not Applicable

#### D.2.c Changes in Other Support

Not Applicable

#### D.2.d New Other Significant Contributors

Not Applicable

#### D.2.e Multi-PI (MPI) Leadership Plan

Not Applicable

**E. IMPACT****E.1 WHAT IS THE IMPACT ON THE DEVELOPMENT OF HUMAN RESOURCES?**

Not Applicable

**E.2 WHAT IS THE IMPACT ON PHYSICAL, INSTITUTIONAL, OR INFORMATION RESOURCES THAT FORM INFRASTRUCTURE?**

NOTHING TO REPORT

**E.3 WHAT IS THE IMPACT ON TECHNOLOGY TRANSFER?**

Not Applicable

**E.4 WHAT DOLLAR AMOUNT OF THE AWARD'S BUDGET IS BEING SPENT IN FOREIGN COUNTRY(IES)?**

NOTHING TO REPORT

## G. SPECIAL REPORTING REQUIREMENTS SPECIAL REPORTING REQUIREMENTS

### G.1 SPECIAL NOTICE OF AWARD TERMS AND FUNDING OPPORTUNITIES ANNOUNCEMENT REPORTING REQUIREMENTS

NOTHING TO REPORT

### G.2 RESPONSIBLE CONDUCT OF RESEARCH

Not Applicable

### G.3 MENTOR'S REPORT OR SPONSOR COMMENTS

Not Applicable

### G.4 HUMAN SUBJECTS

#### G.4.a Does the project involve human subjects?

Not Applicable

#### G.4.b Inclusion Enrollment Data

File(s) uploaded:  
inclusion-enrollment-report\_completed.pdf

#### G.4.c ClinicalTrials.gov

Does this project include one or more applicable clinical trials that must be registered in ClinicalTrials.gov under FDAAA?

### G.5 HUMAN SUBJECTS EDUCATION REQUIREMENT

NOT APPLICABLE

### G.6 HUMAN EMBRYONIC STEM CELLS (HESCS)

Does this project involve human embryonic stem cells (only hESC lines listed as approved in the NIH Registry may be used in NIH funded research)?

No

### G.7 VERTEBRATE ANIMALS

Not Applicable

### G.8 PROJECT/PERFORMANCE SITES

Not Applicable

<b>G.9 FOREIGN COMPONENT</b> No foreign component
<b>G.10 ESTIMATED UNOBLIGATED BALANCE</b> Not Applicable
<b>G.11 PROGRAM INCOME</b> Not Applicable
<b>G.12 F&amp;A COSTS</b> Not Applicable

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## I. OUTCOMES

### I.1 What were the outcomes of the award?

Slip and fall accidents are a major and growing source of occupational injuries. Slip-resistant shoes with a high coefficient of friction (COF) are effective at reducing slipping risk. However, neither experts nor industry has agreed upon a consistent set of criteria for labeling a shoe as slip-resistant. A consequence of this lack of standardization is that significant variability exists across shoes that are labeled slip-resistant. Furthermore, independent testing of shoe COF is expensive, which may limit its use by employers and employees. The proposed research aims to address this problem by developing a predictive model for shoe-floor-contaminant COF based on shoe parameters that can be measured with little cost. The overall objective of this R03 study is to train and validate a statistical model for predicting the COF of footwear against a floor surface in the presence of a liquid contaminant.

Aim 1: Using mechanical friction experiments, we characterized the friction response of 78 shoes including 62 slip-resistant shoe designs and 15 non-slip-resistant shoe designs. A prediction model was developed that predicted 88% of the variability in friction performance across slip-resistant shoes based on the tread surface area, shoe beveling, and hardness, while controlling for the flooring. This model did not apply to non-slip-resistant shoes due to the presence of fluid pressures. Thus, strategies to improve the friction performance of slip-resistant shoes may consider the design parameters utilized in this study, while strategies to improve friction performance of non-slip-resistant shoes should prioritize improving fluid drainage. Safety managers intending to use this model should be aware that it only applies to slip-resistant shoes.

Aim 2: The model was validated based on 38 human slips in oily conditions. The model was found to sensitively predict whether a participant would experience a slip. Thus, the model appeared to provide friction predictions that are relevant to human safety.

This study led to numerous outputs and outcomes. The work was disseminated by 1 published peer-reviewed papers (1 more in review and 2 in preparation) and several presentations that targeted the scientific, footwear producer, and safety professional communities.