Applied Ergonomics 114 (2024) 104110

Contents lists available at ScienceDirect

Applied Ergonomics

journal homepage: www.elsevier.com/locate/apergo

Prospective validity assessment of a friction prediction model based on tread outsole features of slip-resistant shoes

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ARTICLE INFO

Keywords:
Footwear
Slips
Trips
And falls
Friction

ABSTRACT

Shoe outsole design strongly influences slip and fall risk. Certain tread features that can be readily measured have been shown to predict friction performance. This research aimed to replicate those findings and quantify their ability to predict slipping. Participants (n = 34) were exposed to a low friction oil-coated floor surface, while wearing slip-resistant shoes. The coefficient of friction (COF) of each shoe were predicted based on tread surface area, the presence of a bevel, and hardness. The COF was measured, and the slip outcome was determined. Predicted and measured COF were correlated, and measured COF was a sensitive predictor of slip outcome. The relationship of predicted COF on slip outcome was weaker than anticipated and was not statistically significant. This study partially confirmed the ability of previous regression equations to predict COF. However, the effect size was weaker than previously reported and predicted COF was not sensitive for predicting slips.

1. Introduction

Use of high-quality slip-resistant footwear is protective against slip and fall events. Estimates have demonstrated that using footwear with good friction performance reduces slips in work environments from 35 to 70% (Bagheri et al., 2021; Bell et al., 2019; Cockayne et al., 2021; Verma et al., 2011). This is encouraging given that 8% of workplace accidents were due to slip and fall events on the same level in 2019 (prior to the COVID-19 pandemic-related changes to injury causes) (U.S. Department of Labor- Bureau of Labor Statistics, 2020) and that 20% of emergency department visit injuries among adults *under* 65 years are due to falls (Centers for Disease Control, 2021a, b, c). Efforts to improve the friction performance of shoes, therefore, have the potential to broadly impact public safety.

The primary means in which footwear, flooring, and an interfacial fluid influence slipping is by modulating the dynamic coefficient of friction (COF). COF is the ratio of friction to normal force during sliding between the shoe and floor surface. The COF (measured during steady-state sliding) has been shown to be a sensitive predictor of slipping events both in laboratory and working environments (Cockayne et al., 2021; Hanson et al., 1999; Iraqi et al., 2018a; Verma et al., 2011). The COF is influenced by properties of the shoe, floor, and contaminant that form the interface (Grönqvist, 1995; Iraqi et al., 2020; Jones et al., 2018; Li and Chen, 2004; Moore et al., 2012). In particular, COF levels have been found to vary substantially across footwear designs (Blanchette and Powers, 2015; Grönqvist, 1995; Nishi et al., 2022; Yamaguchi et al., 2012, 2017), flooring roughness levels (Chang et al., 2001, 2004; Cowap et al., 2015), and fluid viscosity levels (Beschorner et al., 2009; Jones et al., 2018; Moore et al., 2012).

The friction performance of slip-resistant shoes operating in the presence of oily flooring are primarily dominated by hysteresis friction in the boundary lubrication regime. Evidence of boundary lubrication is based on the minimal fluid pressures observed for new slip-resistant shoes (Beschorner et al., 2014; Hemler et al., 2019; Iraqi et al., 2020; Sundaram et al., 2020). This concept is further supported by experimental and modeling studies demonstrating that shoe features with higher predicted hysteresis friction are well correlated with the COF of the shoe on oily flooring (Jones et al., 2018; Moghaddam and Beschorner, 2018; Yamaguchi et al., 2017). Our team has recently developed a regression equation for shoe-floor COF based on three tread features: tread surface area in the heel region, the presence of a heel bevel, and the hardness of the shoe material (Iraqi et al., 2020). An important methodological choice in Iraqi et al. (2020) was that all of the predictive metrics were evaluated with tools that cost less than US$100 (surface area: ink and paper; heel bevel: visual inspection; hardness: durometer). This prior study demonstrated that the model predicted 87% of the experimentally observed variation with an RMS error of 0.055 (Iraqi et al., 2020). While these results were encouraging, the

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https://doi.org/10.1016/j.apergo.2023.104110
Received 30 January 2023; Received in revised form 20 July 2023; Accepted 9 August 2023
Available online 16 August 2023

conclusions of the study were based on robotic testing of shoe COF and did not evaluate human slipping. Furthermore, there is a need to prospectively evaluate the model as it is applied to more shoe designs and floor surfaces. The present study is aimed at continuing this prior research by determining the prospective validity of the developed model utilizing new shoes. Importantly, this study uses materials (shoe designs and a floor surface) that deviate from those used to train the model. This study also considers a variety of shoe sizes whereas the original study only considered a single shoe size.

The purpose of this study was to prospectively assess the predictive ability of the model from Iraqi et al. (2020) to predict human slips. Our *a priori* hypothesis was that higher COF predicted by the model will predict a reduced risk of slip incidence.

2. Methods

A total of 34 participants were included in this data set. These participants were pooled across two studies with identical data collection methods (Study 1: n = 13 (Beschorner et al., 2023); Study 2: n = 21) (mean/standard deviation age: 31/13 years; height: 1.71/0.09 m; weight: 72.5/12.2 kg; 15 women, 19 men). Inclusion criteria for both studies included adult age (>18 years), weight under 114 kg, and height under 193 cm. Exclusion criteria included obesity (body mass index >30), any medical conditions that would affect walking (e.g., lower-body arthritis), or increase injury risk associated with a slip (e.g., osteoporosis). In Study 1, only a subset of the participants (those exposed to oil on a porcelain tile floor surface) were included in this analysis to ensure consistency with Study 2. In addition to the included 34 participants, 8 participants (n = 4 from the 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), and the participant not stepping in the contaminant (n = 1).

A database of footwear identified as slip-resistant by their manufacturer was curated that included 19 different brands prior to data collection (Table 1). Participants were randomly matched with footwear, ensuring that they received footwear consistent with their reported gender and shoe size. In some cases, footwear models on the curated list were discontinued. When this happened, a shoe in the database was replaced with a similar available shoe by the research team. The choice to only have one participant per shoe design was intended to meet the statistical assumptions of independence between observations and to improve the generalizability of the results to the full population of slip-resistant shoes. None of the shoe models nor the flooring materials used in the development of the statistical model (Iraqi et al., 2020) were used in this prospective validation.

Participants donned slip-resistant shoes, a safety harness, and a set of 79 motion capture markers (collected at 120 Hz by 14 Vicon T40S cameras, Denver, CO) (Moyer, 2006). 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 measured from a force plate (collected at 1080 Hz, Bertec Corporation, Columbus, OH, USA). During the trials, participants were instructed to walk at an urgent yet comfortable pace. During the dry trials, the participants' starting position was altered to align their foot placement with the region of the floor where the contaminant would be applied during the slipping trial. Participants were not provided with any instruction on foot placement during the trials. After about 10 dry trials were completed, canola oil was poured (as opposed to sprayed or squirted (Chimich et al., 2022)) on a floor tile without the awareness of the participant. Each participant completed a single trial where they walked on the oily surface. To reduce awareness of the floor condition, participants faced away from the walkway, listened to music, and completed a task between trials. Furthermore, room lighting was kept low (0.38 lux intensity, 3250 K color) to reduce visual cues of the contaminant.

Table 1
Manufacturer and style names for the shoes included in the study (sorted by Manufacturer).

Gender	Manufacturer	Style	Model	Size[a]
W	Adidas	Originals Superstar	N/A	9
W	Crocs	Bistro	10075–001	6
M	Dockers	Director II	90–58214	11
M	Dr Scholl's	Men's Proudest Slip Resistant Cap Toe Oxford	88626	11
W	Dr Scholl's	Women's Kimberly II Medium/Wide Slip Resistant Sneaker	88755	7.5
M	Dr Scholl's	Men's Hiro Memory Foam Slip Resistant Oxford	25318	9
M	Interceptor	Interceptor Men's Canton Waterproof Work Boots, Slip Resistant, Black	556707644	10.5
M	Keen	Men's Braddock Waterproof Mid (Soft Toe)	1014605	12
M	Keen	MEN'S PTC DRESS OXFORD	1006981	13
W	Lila	Kavina	36907	7.5
W	Merrell	Jungle MOC AC + Pro	J45360	6.5
W	Mozo-Shoes for Crews	Maven	M33738	6.5
M	PF Flyers	Sandlot Center Lo	44520	10
M	Reebok	Sublite Cusion Work	SRB 3200	9
M	Reebok	Senexis	SRB 1020	10
M	Rockport	Sailing Club Maxtrax	RK2220	9.5
M	safeTstep	Men's Slip Resistant Halfpipe Canvas Oxfords	166413	9.5
M	Shoes for Crews	Dolce	76236	12
M	Shoes for Crews	Cambridge	6006	10
W	Shoes for Crews	Heather	9048	6.5
M	Shoes for Crews	Delray - Canvas	38852	10
W	Skechers	Ghenter-Bronaugh	77210	6
W	Skechers	Sudler	681837792	8.5
W	Skechers	Sudler	77245	8.5
M	Skechers	Felton- Altair	77032	10.5
W	SRmax	Arlington Women's Slip Resistant Dress Oxford	SRM350	6.5
M	SRMax	Rialto	SRM600	9
W	Tanleewa	OwnShoe Sunbrella	TW-005	8.5
W	Tanleewa	OwnShoe	TW-001	9
W	Tanleewa	OwnShoe Sunbrella	TW-005	7
M	Tredsafe	Men's Executive II Slip-Resistant Work Shoe	570506609	7.5
W	Tredsafe	Cat	0051	8
M	Tredsafe	Trevor	576890265	10
W	Vangelo	Ritz	D808624	7

[a] United States shoe sizes which contains separate scales for men and women. The scale utilized was consistent with the manufacturer-reported gender of the shoe.

Two biomechanical variables were extracted from the human participant data: slip outcome from the unexpected slip trial and RCOF from the baseline walking trials (MATLAB, MathWorks, Natick, MA). Slip outcome (i.e., heel slip outcome) was evaluated based on the calculated displacement of the heel marker between slip onset and the end of a slip (Beschorner et al., 2019; Iraqi et al., 2018a; Jones et al., 2018). Slip onset was determined as the local minimum in slipping speed of the heel marker 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 (Beschorner et al., 2019; Iraqi et al., 2018a; Jones et al., 2018). RCOF was measured to control for varying risk specific to each individual's gait style (Beschorner et al., 2016). While other biomechanical variables have been associated with slipping risk, prior research has demonstrated that RCOF is typically the mechanistic pathway by which these factors influence slip and fall risk (Espy et al., 2010; Lockhart et al., 2003; Moyer et al., 2006). The RCOF was based on the greatest local maximum for the ratio of friction to normal force when the following conditions were met (Beschorner et al., 2016; Chang et al., 2011): 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. Ground reaction force data were filtered using a fourth-order low-pass filter with a cutoff frequency of 36 Hz and kinematic data was filtered using a fourth-order low-pass filter with a cutoff frequency of 6 Hz (Beschorner et al., 2016).

Predicted COF values were based on the tread outsole features surface area and 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.

$$COF_{Predicted} = 0.223 + 0.015 * \text{tread surface area}\left[\text{cm}^2\right] + 0.041 * \text{heel shape[bevel]} - 0.003 * \text{hardness [Shore A]} \quad \text{Eq. (1)}$$

(Excel, Microsoft, Redmond, WA). 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 the same methods as Iraqi et al. (2020). The tread surface area was measured by coating the tread with ink, making an imprint while pressing down on the insole, scanning the imprint, and then summing the contact area in the posterior 50 mm region of the imprint. When making the imprint, a combination of pressing and rolling the shoe was performed since many of the shoes had curved heels. At each orientation, pressure was applied with a finger to the insole. After this pressure was applied, the shoe was iteratively rolled to another orientation and pressure was applied again until an imprint of the full heel region was obtained. To obtain just the posterior 50 mm of the heel region, the image of the surface area was cropped to remove parts of the image more than 50 mm anterior of the back of the heel. 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 slightly from that described in Iraqi et al. (2020) 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 above 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. 1). COF was predicted using Eq. (1) where the parameters in brackets were the units in the case of tread

Fig. 1. The test used to assess whether shoes contained a bevel. The back of the heel and the back of the USB latches (rectangular holes) were aligned with the side of a table. If there was enough space to accommodate the portion of the USB port in front of the latches, the shoe was considered to be beveled.

COF values were measured using a robotic slip tester (STEPS device, XRDS Systems, Nashua, NH) for each shoe in the study. The robotic slip tester had a horizontal motor, that slid the shoe against the floor surface, a vertical motor that applied the vertical load, and a force plate for measuring ground reaction forces in the shear/horizontal plane and normal/vertical direction. The forces were recorded at 1000 Hz. The shoe-floor angle was set to 17° (toe up, ±1°) relative to the orientation of the shoe when placed on a level surface. The shoe was then slid across the floor surface at a speed of 0.5 m/s (±0.05 m/s) and a normal load of 250 N (±25 N). These test conditions are based on previous research identifying them to reflect the biomechanical conditions of slipping and to be predictive of slip outcomes (Beschorner et al., 2023; Iraqi et al., 2018a, 2018b; Sundaram et al., 2020). The floor tile (Galaxy Stone YV600940, Dongpeng Ceramic Co, Foshan, China) was contaminated with canola oil with the same application method as in the unexpected slip trials. COF was calculated as the average resultant shear force to normal force for 50 ms after the shoe first sustained a load of 250 N (Beschorner et al., 2020) (STEPS, Johnstown, PA). The average COF of 3 trials was calculated. Two shoes were excluded from measurement due to being too small to fit on the last used in the device.

Univariate and multivariate logistical regression models were used to assess whether the COF prediction model was associated with slips (JMP Pro 16, SAS Institute, Cary, NC). 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 was reported. A sample size of 46 human slips was originally planned to achieve a power of 95% in the univariate analysis assuming the mean COF was associated with a slip rate of 50% and the slip rate dropped to 20% at one standard deviation above the mean COF. The final sample size ($n = 34$) led to a power of 84% using the same assumptions.

Statistical analyses were also performed to verify whether the predicted COF was correlated with measured COF and whether the measured COF was predictive of slip outcome. A bivariate correlation analysis was performed with measured COF as the dependent variable and predicted COF as the independent variable. A multivariate correlation analysis was performed to determine the contribution of contact area, shoe bevel, and material hardness on measured COF. A univariate logistic regression analysis was performed with measured COF as the independent variable and slip outcome as the dependent variable. Type 1 error rate (α) was set to 0.05 for all analyses.

3. 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^2 (3.3 cm^2) for tread surface area and 59.1 (7.1) for hardness. Bevels were present on 26 of the shoes (68%). Of the 34 participants, 10 experienced slips (29%). The mean (standard deviation) of RCOF and measured COF was 0.198 (0.040) and 0.133 (0.056), respectively.

Shoes with a larger predicted COF value were associated with a

Table 2
Results of the univariate and multivariate models. No hypothesis testing was performed for the intercept and so no p-value is provided. AUC refers to the area under the receiver operating characteristic curve. The β values refer to the coefficients in the regression equations provided in the footnotes.

Statistical Model	Independent Variable	β	p-value	AUC
Univariate	Intercept	−1.4[a]	*	0.600
	$COF_{Predicted}$	9.6[a]	0.184	
Multivariate	Intercept	0.8[b]	*	0.729
	$COF_{Predicted}$	10.2[b]	0.175	
	RCOF	−12.0[b]	0.212	

*Significance was not determined for the intercept variable.

[a] $P(slip) = \frac{1}{1 + e^{\beta_{Intercept} + \beta_{COF_{Predicted}} * COF_{Predicted}}}$.

[b] $P(slip) = \frac{1}{1 + e^{\beta_{Intercept} + \beta_{COF_{Predicted}} * COF_{Predicted} + \beta_{RCOF} * RCOF}}$.

reduction in slip outcome but the effect did not reach statistical significance for either the univariate and multivariate statistical models (Table 2). The univariate model indicated that an increase in COF was associated with a non-significant reduction in slip risk ($p = 0.184$, $\chi^2_{(1)} = 1.8$) (Fig. 2). The odds ratio across a standard deviation in predicted COF (COF increase of 0.045) and the interquartile range of predicted COF (COF increase of 0.067) was 0.719 (95% confidence interval: 0.333 to 1.262) and 0.612 (95% confidence interval: 0.195 to 1.414), respectively. The area under the receiver operating characteristic curve was 0.600. The multivariate model also yielded that the predicted COF was negatively associated with slipping but lacked significance ($p = 0.175$, $\chi^2_{(1)} = 1.8$). The multivariate model also yielded a non-significant effect for RCOF ($p = 0.212$, $\chi^2_{(1)} = 1.6$).

Supplementary statistical analyses revealed that the predicted COF correlated with the measured COF and that measured COF predicted slip risk. The measured COF was positively correlated with the predicted COF ($r = 0.5$, $t_{30} = 0.317$, $p = 0.004$) (Fig. 3A). The intercept was approximately 0 and the slope of the prediction line was 0.5 suggesting that the measured COF was scaled relative to the predicted value. The root mean square error of the bivariate regression model was 0.049. The measured COF was found to be positively correlated with shoe bevel, negatively correlated with hardness, and positively but insignificantly correlated with tread surface area (Table 3). The correlation coefficients for the model were similar to the model developed by Iraqi et al. except that the surface area coefficient was smaller than previously indicated. The model achieved an R^2 of 0.340 and an RMS error of 0.048. An increase in the measured COF was associated with a reduction in slip outcome ($p = 0.009$, $\chi^2_{(1)} = 6.9$) (Fig. 3B).

4. Discussion

This preliminary validation study offered mixed results regarding the predictive ability of COF predictions based on contact area, bevel, and hardness. While the predicted COF did not reach statistical significance in its predictions of slip outcome, the observed effect was in the hypothesized direction (higher predicted COF associated with reduced slip risk). Furthermore, the odds ratio (0.72 across a standard deviation of COF) was small (Chen et al., 2010) but meaningful magnitude and the predicted COF was correlated with the measured COF. Retraining the model did not meaningfully improve it since it yielded similar regression coefficients (Table 3) and a similar RMS error (0.048 vs 0.055) as the model predictions from the prior study. The results confirmed the pathway by which predicted COF was expected to influence slip outcomes (i.e., predicted COF was positively associated with measured COF, which was negatively associated with slip outcome). Thus, the lack of significance for the primary logistic regression analyses may be the result of Type II error as opposed to indicating a lack of effect. Type II error occurs naturally in all research studies but was increased in the present study because a lower sample size was collected than originally planned. Nonetheless, the weaker effect of the predicted COF compared with the measured COF is notable. Overall, this study suggests that a small benefit (increased friction and reduced slip risk) is associated with slip-resistant shoes that have high hysteresis friction through increased surface area, the presence of a bevel, and reduced hardness.

This study builds and clarifies the results of our prior study that demonstrated that these three tread features were associated with friction (Iraqi et al., 2020). Performing replication studies using different methods is an advisable way to demonstrate the robustness of research results (Wasserstein et al., 2019). This study deviated from the prior study by using different shoes, a different floor surface, and a different outcome measure (slip outcome in addition to measured COF). While both studies agreed that the measured coefficient of friction could be

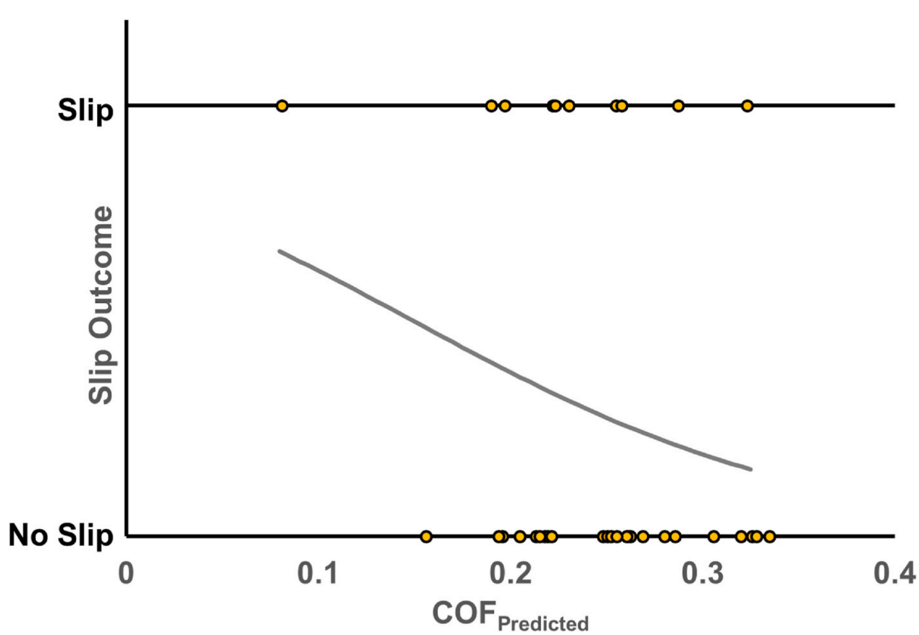

Fig. 2. The logistic regression plot for the univariate analysis where slip outcome is fit by the predicted COF values from the model. Each point represents the outcome from an individual participant, while the line represents the fit line.

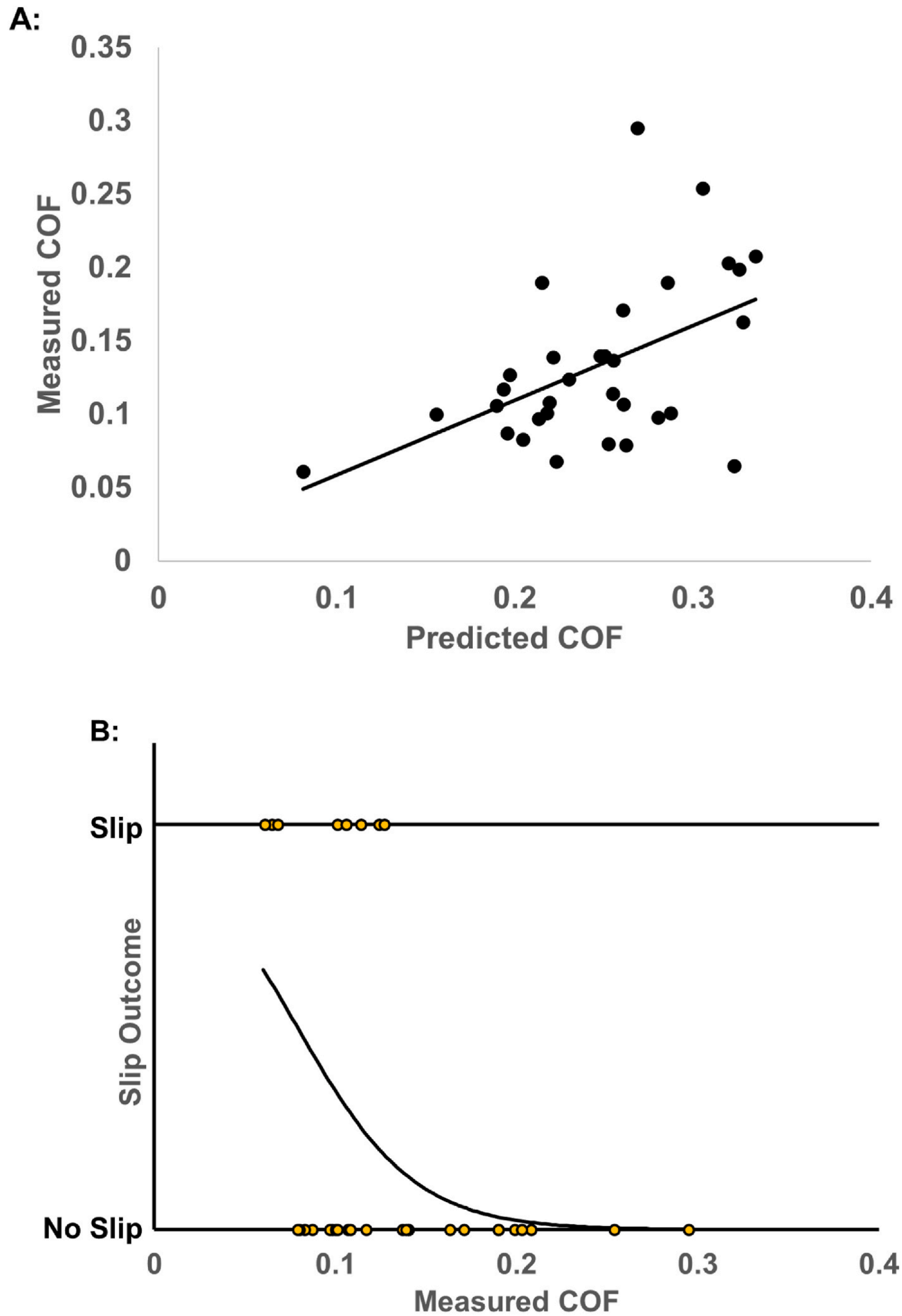

Fig. 3. A: Scatter plot of the measured COF plotted against the predicted COF. The black line represents the linear fit (r = 0.5). B: The logistic regression analysis between the measured COF and the slip outcome.

Table 3
Regression model as reported by Iraqi et al. (2020) (column 2) and in the present study (columns 3–5).

Regressor [units]	Iraqi et al. (2020)	Current Study		
	Coefficient (Standard Error)		t-value (df = 28)	p-value
Tread Surface Area [cm^2]	0.015 (0.003)	0.004 (0.003)	1.48	0.150
Bevel	0.041 (0.012)	0.037 (0.018)	2.07	0.048
Hardness (Shore A)	−0.003 (0.001)	−0.004 (0.001)	−2.77	0.010

predicted based on the tread surface area, shoe bevel, and hardness, the current study observed a notably weaker relationship (r = 0.50) than observed in the prior study (R = 0.93) (Iraqi et al., 2020). Some methodological differences may explain the difference in the strength of the correlation. First, Iraqi et al. performed a fit on two floor surfaces with a nominal variable representing the floor surface. Therefore, this study was also capturing the variance across the two floor surfaces. Second, the current study was a prospective validation, whereas Iraqi et al. was fitting a model to data retrospectively. Third, Iraqi et al., used different models from across 6 brands whereas the current study included shoes from across 19 different brands. The increased brand heterogeneity of the current study may have introduced additional variability (e.g., viscoelastic material properties (Ido et al., 2019; Jakobsen et al., 2021; Yamaguchi et al., 2020)) that were not captured by our model. Even though Iraqi et al. (2020) and the present study differed in the strength of the relationship, they were consistent regarding the existence of a relationship. Other studies have similarly found that a reduction in contact area due to tread bending is associated with a loss in friction (Yamaguchi et al., 2017), and the mechanism may be the pressure dependence of elastomers that can be modeled with finite element analysis (Moghaddam et al., 2018). Therefore, the results of this study are generally consistent with prior research and current mechanics understanding of shoe-floor friction.

This study provides modest justification for footwear manufacturers and consumers to alter their behavior around designing and selecting footwear, respectively. Footwear design is a particularly attractive modifiable risk factor because it can be altered without the need for flooring renovations or redesigning the job that is being performed. Despite the weaker than expected trends, there still appears to be evidence to support footwear designers' efforts to enhance the three design features that are part of the shoe predictive model. However, this may only be advisable when making these design changes would not lead to other safety hazards. For example, tread surface area can only be increased so much before encroaching the tread channels or going outside of the shoe form. Reducing tread channels will, at some point, increase hydrodynamic pressures offsetting the benefit of reduced contact pressures (Hemler et al., 2020; Walter et al., 2021). Going outside of the shoe form may potentially increase trip risk. Reducing the hardness of the shoe material is believed to improve friction by enabling more deformation in the shoe tread, spreading the contact over a larger region, and reducing the contact pressures (Grönqvist, 1995; Tsai and Powers, 2008; Walter et al., 2021). Prior modeling studies have demonstrated this pathway as capable of increasing COF (Moghaddam and Beschorner, 2015; Moghaddam et al., 2018). Making material formulation changes to alter the hardness, however, may have unintended consequences including altering the viscoelastic properties (i.e., by potentially reducing tangent modulus) and offsetting the benefits of the lower hardness on hysteresis friction. 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. First, the study was not powered to the *a priori* number of participants (in part because of lab shutdowns during the COVID-19 pandemic). The results of this study suggest that the lack of significance may be due to Type II error. Given the observed effect sizes (that were weaker than anticipated) and the observed slip rates (that were lower than anticipated) in the present study, future similar studies would require more participants to power these analyses: 118 participants (Power = 0.80, one-tailed test), 201 participants (Power = 0.95, one-tailed test), 151 participants (Power = 0.80, two-tailed test), or 243 participants (Power = 0.95, two-tailed test). Second, 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 does not apply to shoes operating in the presence of fluid pressures (Meehan et al., 2022). 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 prospectively predict COF but did not have a strong enough effect to predict slip outcomes in the current study's sample size. This study clarifies that the previously developed model can prospectively predict shoe-floor COF but with weaker correlation than previously quantified. Therefore, the present study suggests that these 3 shoe parameters (tread surface area, heel beveling, and material hardness) can be modified to modestly influence slip and fall risk. The implementation of this knowledge is expected to modestly reduce the burden of slip and fall injuries.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study was funded by the National Institute for Occupational Safety and Health (R03 OH011069), the National Institute on Aging (R44 AG059258), and the National Center for Research Resources (S10RR027102). The authors would also like to acknowledge Claire Tushak and Sarah Delahunt for their contributions with data collection.

References

Bagheri, Z.S., Beltran, J.D., Holyoke, P., Dutta, T., 2021. Reducing fall risk for home care workers with slip resistant winter footwear. Appl. Ergon. 90, 103230.
Bell, J.L., Collins, J.W., Chiou, S., 2019. Effectiveness of a no-cost-to-workers, slip-resistant footwear program for reducing slipping-related injuries in food service workers: a cluster randomized trial. Scand. J. Work. Environ. Health 45.
Beschorner, K., Lovell, M., Higgs III, C.F., Redfern, M.S., 2009. Modeling mixed-lubrication of a shoe-floor interface applied to a pin-on-disk apparatus. Tribol. Trans. 52, 560–568.
Beschorner, K.E., Albert, D.A., Chambers, A.J., Redfern, M.R., 2014. Fluid pressures at the shoe-floor-contaminant interface during slips: effects of tread & implications on slip severity. J. Biomech. 47, 458–463.
Beschorner, K.E., Albert, D.L., Redfern, M.S., 2016. Required coefficient of friction during level walking is predictive of slipping. Gait Posture 48, 256–260.
Beschorner, K.E., Chanda, A., Moyer, B.E., Reasinger, A., Griffin, S.C., Johnston, I.M., 2023. Validating the ability of a portable shoe-floor friction testing device, NextSTEPS, to predict human slips. Appl. Ergon. 106, 103854.
Beschorner, K.E., Iraqi, A., Redfern, M.S., Cham, R., Li, Y., 2019. Predicting slips based on the STM 603 whole-footwear tribometer under different coefficient of friction testing conditions. Ergonomics 62, 668–681.
Beschorner, K.E., Iraqi, A., Redfern, M.S., Moyer, B.E., Cham, R., 2020. Influence of averaging time-interval on shoe-floor-contaminant available coefficient of friction measurements. Appl. Ergon. 82, 102959.
Blanchette, M.G., Powers, C.M., 2015. The influence of footwear tread groove parameters on available friction. Appl. Ergon. 50, 237–241.
Centers for Disease Control, 2021a. In: Services, H.a.H. (Ed.), 10 Leading Causes of Injury Deaths by Age Group Highlighting Unintentional Injury Deaths, United States - 2019 (Atlanta, GA).
Centers for Disease Control, 2021b. Overall all injury causes nonfatal emergency department visits and rates per 100,000; 2019, United States, all races, both sexes. In: Services, H.a.H. (Ed.), Ages 18 to 65; Disposition: All Cases (Atlanta, GA).
Centers for Disease Control, 2021c. Overall all injury causes nonfatal emergency department visits and rates per 100,000; 2019. In: Services, H.a.H. (Ed.), United States, All Races, Both Sexes, Ages 18 to 65; Disposition: Falls (Atlanta, GA).
Chang, W.-R., Chang, C.-C., Matz, S., 2011. The effect of transverse shear force on the required coefficient of friction for level walking. Hum. Factors: The Journal of the Human Factors and Ergonomics Society 53, 461–473.
Chang, W.-R., Grönqvist, R., Hirvonen, M., Matz, S., 2004. The effect of surface waviness on friction between Neolite and quarry tiles. Ergonomics 47, 890–906.
Chang, W.-R., Kim, I.-J., Manning, D.P., Bunterngchit, Y., 2001. The role of surface roughness in the measurement of slipperiness. Ergonomics 44, 1200–1216.
Chen, H., Cohen, P., Chen, S., 2010. How big is a big odds ratio? Interpreting the magnitudes of odds ratios in epidemiological studies. Communications in Statistics—simulation and Computation® 39, 860–864.
Chimich, D.D., Al-Salehi, L., Elkin, B.S., Siegmund, G.P., 2022. Contaminant film thickness affects walkway friction measurements. Front. Public Health 10, 915140-915140.
Cockayne, S., Fairhurst, C., Frost, G., Liddle, M., Cunningham-Burley, R., Zand, M., Hewitt, C., Iles-Smith, H.M., Green, L., Torgerson, D.J., 2021. Slip-resistant footwear reduces slips among National Health Service workers in England: a randomised controlled trial. Occup. Environ. Med. 78, 472–478.
Cowap, M., Moghaddam, S., Menezes, P., Beschorner, K., 2015. Contributions of adhesion and hysteresis to coefficient of friction between shoe and floor surfaces: effects of floor roughness and sliding speed. Tribol. Mater. Surface Interfac. 9, 77–84.
Espy, D.D., Yang, F., Bhatt, T., Pai, Y.-C., 2010. Independent influence of gait speed and step length on stability and fall risk. Gait Posture 32, 378–382.
Grönqvist, R., 1995. Mechanisms of friction and assessment of slip resistance of new and used footwear soles on contaminated floors. Ergonomics 28, 224–241.
Hanson, J.P., Redfern, M.S., Mazumdar, M., 1999. Predicting slips and falls considering required and available friction. Ergonomics 42, 1619–1633.

Hemler, S., Charbonneau, D., Beschorner, K., 2020. Predicting hydrodynamic conditions under worn shoes using the tapered-wedge solution of Reynolds equation. Tribol. Int., 106161
Hemler, S., Charbonneau, D., Iraqi, A., Redfern, M.S., Haight, J.M., Moyer, B.E., Beschorner, K.E., 2019. Changes in under-shoe traction and fluid drainage for progressively worn shoe tread. Appl. Ergon. 80, 35–42.
Ido, T., Yamaguchi, T., Shibata, K., Matsuki, K., Yumii, K., Hokkirigawa, K., 2019. Sliding friction characteristics of styrene butadiene rubbers with varied surface roughness under water lubrication. Tribol. Int. 133, 230–235.
Iraqi, A., Cham, R., Redfern, M.S., Beschorner, K.E., 2018a. Coefficient of friction testing parameters influence the prediction of human slips. Appl. Ergon. 70, 118–126.
Iraqi, A., Cham, R., Redfern, M.S., Vidic, N.S., Beschorner, K.E., 2018b. Kinematics and kinetics of the shoe during human slips. J. Biomech. 74, 57–63.
Iraqi, A., Vidic, N.S., Redfern, M.S., Beschorner, K.E., 2020. Prediction of coefficient of friction based on footwear outsole features. Appl. Ergon. 82, 102963.
Jakobsen, L., Lysdal, F.G., Sivebaek, I.M., 2021. Dynamic mechanical analysis as a predictor for slip resistance and traction in footwear. Footwear Sci. 13, S57–S58.
Jones, T.G., Iraqi, A., Beschorner, K.E., 2018. Performance testing of work shoes labeled as slip resistant. Appl. Ergon. 68, 304–312.
Li, K.W., Chen, C.J., 2004. The effect of shoe soling tread groove width on the coefficient of friction with different sole materials, floors, and contaminants. Appl. Ergon. 35, 499–507.
Lockhart, T.E., Woldstad, J.C., Smith, J.L., 2003. Effects of age-related gait changes on the biomechanics of slips and falls. Ergonomics 46, 1136–1160.
Moghaddam, S.R., Beschorner, K.E., 2015. Multiscale Computational Modeling of Shoe-Floor Hysteresis Friction. American Society of Biomechanics, Columbus, OH.
Meehan, E.E., Vidic, N.S., Beschorner, K.E., 2022. In contrast to slip-resistant shoes, fluid drainage capacity explains friction performance across shoes that are not slip-resistant. Appl. Ergon. 100, 103663.
Moghaddam, S.R.M., Acharya, A., Redfern, M.S., Beschorner, K.E., 2018. Predictive multiscale computational model of shoe-floor coefficient of friction. J. Biomech. 66, 145–152.
Moghaddam, S.R.M., Beschorner, K.E., 2018. Predicting shoe-floor contact pressures and their impact on coefficient of friction using finite element analysis. Tribol. Lubric. Technol. 74, 26–28.
Moore, C.T., Menezes, P.L., Lovell, M.R., Beschorner, K.E., 2012. Analysis of shoe friction during sliding against floor material: role of fluid contaminant. J. Tribol. 134, 041104.
Moyer, B., 2006. Slip and Fall Risks: Pre-slip Gait Contributions and Post-Slip Response Effects. University of Pittsburgh, Pittsburgh.
Moyer, B., Chambers, A., Redfern, M.S., Cham, R., 2006. Gait parameters as predictors of slip severity in younger and older adults. Ergonomics 49, 329–343.
Nishi, T., Yamaguchi, T., Hokkirigawa, K., 2022. Development of high slip-resistant footwear outsole using rubber surface filled with activated carbon/sodium chloride. Sci. Rep. 12, 1–12.
Sundaram, V., Hemler, S.L., Chanda, A., Haight, J.M., Redfern, M.S., Beschorner, K.E., 2020. Worn region size of shoe soles impacts human slips: testing a mechanistic model. J. Biomech., 109797
Tsai, Y.J., Powers, C.M., 2008. The influence of footwear sole hardness on slip initiation in young adults. J. Forensic Sci. 53, 884–888.
U.S. Department of Labor- Bureau of Labor Statistics, 2020. Nonfatal Cases Involving Days Away from Work: Selected Characteristics (2011 Forward) Series ID: CSUE4X00000063000, CSUE4200000063000, CSU00X00000063000. CSU00X422XXX6E000, Washington, D.C.
Verma, S.K., Chang, W.R., Courtney, T.K., Lombardi, D.A., Huang, Y.-H., Brennan, M.J., Mittleman, M.A., Ware, J.H., Perry, M.J., 2011. A prospective study of floor surface, shoes, floor cleaning and slipping in US limited-service restaurant workers. Occup. Environ. Med. 68, 279–285.
Walter, P.J., Tushak, C.M., Hemler, S.L., Beschorner, K.E., 2021. Effect of tread design and hardness on interfacial fluid force and friction in artificially worn shoes. Footwear Sci. 13, 245–254.
Wasserstein, R.L., Schirm, A.L., Lazar, N.A., 2019. Moving to a World beyond "P< 0.05". Taylor & Francis.
Yamaguchi, T., Katsurashima, Y., Hokkirigawa, K., 2017. Effect of rubber block height and orientation on the coefficients of friction against smooth steel surface lubricated with glycerol solution. Tribol. Int. 110, 96–102.
Yamaguchi, T., Pathomchat, P., Shibata, K., Nishi, T., Tateishi, J., Hokkirigawa, K., 2020. Effects of porosity and SEBS fraction on dry sliding friction of EVA foams for sports shoe sole applications. Tribol. Trans. 63, 1067–1075.
Yamaguchi, T., Umetsu, T., Ishizuka, Y., Kasuga, K., Ito, T., Ishizawa, S., Hokkirigawa, K., 2012. Development of new footwear sole surface pattern for prevention of slip-related falls. Saf. Sci. 50, 986–994.