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ORIGINAL PAPER

# Analysis of the Contribution of Adhesion and Hysteresis to Shoe–Floor Lubricated Friction in the Boundary Lubrication Regime

**Caitlin Moore Strobel · Pradeep L. Menezes · Michael R. Lovell · Kurt E. Beschorner**

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**Abstract** Slip and fall accidents cause frequent occupational injuries. Despite recent evidence that boundary lubrication is relevant to slipping, few studies have examined the mechanisms that contribute to shoe–floor friction in this lubrication regime. This study aims to identify the contributions of adhesion and hysteresis to friction in boundary lubrication. Three shoe materials (40 Shore A hardness polyurethane, 60 Shore A hardness rubber, and 70 Shore A hardness rubber), two floor materials (vinyl and marble), and six lubricants (water, 1.5 % detergent, 25 % glycerol–75 % water, 50 % glycerol–50 % water, 75 % glycerol–25 % water, and canola oil) were tested at a single sliding speed (0.01 m $s^{-1}$). Dry adhesion and hysteresis were quantified for each of the shoe–floor combinations and lubricated adhesion was quantified for all shoe–floor-fluid combinations. The contribution of adhesion and hysteresis to shoe–floor-lubricant friction was affected by both the shoe and floor material due to differences in hardness and roughness. Lubricated adhesion was complex and multifactorial with contributions from the shoe, fluid, shoe–floor interaction, floor-lubricant interaction, and shoe-lubricant interactions. A simple regression model including two fluid coefficients and the dry adhesion friction force was able to predict 49 % of the lubricated adhesion friction variability.

**Keywords** Shoe–floor friction · Boundary lubrication · Adhesion · Hysteresis

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**Abbreviations**

| | |
|---|---|
| $FF$ | Friction force ($N$) measured between shoe and floor material |
| $R_q$ (μm) | RMS roughness |
| $FF_{BL}$ | $FF$ under boundary lubrication |
| $FF_{adhesion}$ | Contribution of adhesion to friction force |
| $FF_{hysteresis}$ | Contribution of hysteresis to friction force |
| $R_a$ | Arithmetic mean of surface profile |
| $R_z$ | Maximum peak to valley height |
| $R_p$ | Maximum profile peak height |
| $R_t$ | Total height of profile |

## 1 Introduction

In the United States, fall accidents cost approximately $13.9 billion in 2007 [1]. It is estimated that approximately 40–50 % of occupational falls are slip induced [2]. Typically a slip occurs when the coefficient of friction required for gait, which generally ranges between 0.17 and 0.22 [3], is greater than the coefficient of friction available between the shoe and floor [4]. It is estimated that 79 % of slips are due to improper floor or shoe materials [5]. Understanding the mechanisms which govern shoe–floor-lubricant friction is essential in improving shoe and floor design and ultimately preventing these injuries.

Shoe–floor-lubricant friction decays with increasing speed following the Stribeck effect, operating primarily in the boundary and mixed-lubrication regimes [6]. Previous work by this research group [6] has examined and modeled fluid pressure effects relevant to shoe–floor-lubricant friction in the mixed-lubrication regime. However, the shoe–floor-lubrication friction mechanisms relevant to boundary lubrication friction have received minimal attention. Emerging research on the topic suggests that boundary

lubrication effects alone can cause substantial reductions in friction [7].

The major contributing factors to dry shoe and floor friction are often considered to be adhesion, tearing, and hysteresis, while lubricated friction is dependent on boundary lubrication [7] and hydrodynamic effects (squeeze-film and wedge effect) [8]. Determining the mechanisms that contribute to shoe–floor-contaminant friction under boundary lubrication is critical to improve existing shoe–floor-contaminant friction models [9] and developing slip-resistant shoes and flooring.

The purpose of this research is to quantify the relative contributions of adhesion and hysteresis to boundary lubricated shoe and floor surfaces. Specifically, the effects of different shoe and floor materials on adhesion and hysteresis and the role of different fluids in blocking shoe–floor adhesion will be quantified.

## 2 Methods

### 2.1 Apparatus and Materials

Experiments were conducted using a custom-developed pin-on-disk type tribometer as presented in Fig. 1a and b. The floor material (disk) was mounted on a rate table and the shoe material (pin) was mounted on a shaft and bearing couple. A normal load is applied to a shaft directly above the pin. When the rate table rotates relative to the fixed shoe material (pin) the frictional force is recorded by load cells.

Three shoe materials, polyurethane (40 Shore A hardness) and two rubber materials (60 and 70 Shore A hardness) were examined. Shoe material specimens were all 10 mm diameter circular samples and untreaded. Commercially available vinyl tile (99 Shore A hardness) and marble tile ($\gg$100 Shore A hardness) samples (304.8 mm $\times$ 304.8 mm $\times$ 35 mm in dimensions) were tested. A durometer was used to measure the hardness of each shoe and floor sample on a Shore A scale of 1–100. The hardness of the marble sample greatly exceeded the Shore A scale. Therefore, the effect of varying the ratio of shoe to floor hardness is discussed qualitatively. The ratio of shoe hardness to floor hardness would be greatest for 70 Shore A hardness rubber to vinyl tile contact and smallest for polyurethane to marble tile contact.

In addition to material hardness, the roughness of the shoe and floor material samples was measured. Preliminary experiments revealed that material properties and surface structure could not be varied independently and the harder shoe materials tended to be less rough than the softer shoe materials. In order to quantify material roughness, a 2D contact type stylus profilometer was used to measure surface roughness parameters of all materials. The variables presented are the arithmetic mean ($R_a$), the maximum peak to valley height ($R_z$), the maximum profile peak height ($R_p$), and the total height of the profile ($R_t$) using a cutoff length of 0.8 mm.

Eight lubrication conditions were examined: dry (unlubricated), water (0.52 cP), 1.5 % diluted detergent (1.8 cP), 25 % glycerol–75 % water (1.9 cP), 50 % glycerol–50 % water (5.54 cP), 75 % glycerol–25 % water (41 cP), canola oil (74.6 cP), and SAE 75W-140 gear oil (376.5 cP). Some lubricants were selected based on their relevance to a slip and fall accident (water, detergent, vegetable oil). Other lubricants were chosen so that their fluid properties could be easily controlled (diluted glycerol concentrations). The dry and SAE gear oil were used to quantify the amount of friction due to hysteresis and adhesion as described in Sect. 3.3.

### 2.2 Experiments

Tests were carried out under a normal load of 20.9 N in ambient conditions, resulting in a biofidelic contact pressure of approximately 266.1 kPa [10], and at a single

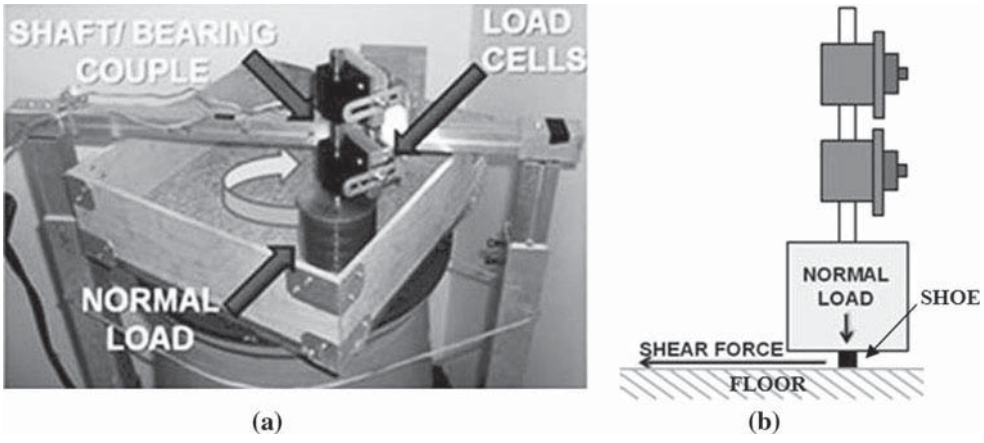


**Fig. 1** Custom pin-on-disk tribometer used to measure shoe–floor-contaminant friction **a** photograph, **b** schematic showing floor material (*disk*), shoe material (*pin*), and direction of shear and normal

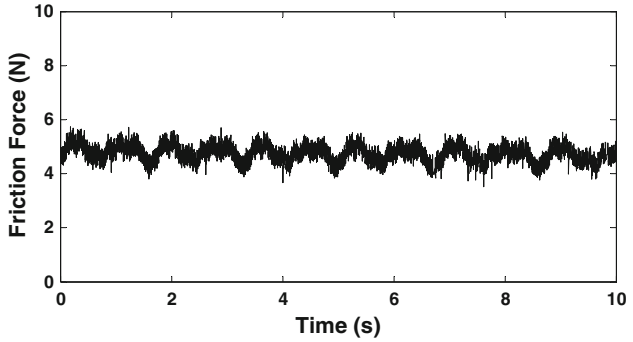


**Fig. 2** Typical time-history of friction force during experiment

sliding speed of 0.01 m $s^{-1}$ selected to be low enough to ensure boundary lubrication. Shoes were conditioned with 220 grit sand paper between each measurement to ensure that the shoe roughness was consistent across trials. Each trial lasted for 10 s and the frictional force was recorded once steady state friction force was achieved (Fig. 2). Between trials, fluids were completely cleaned from the surface with detergent and water and then were rinsed with water. Under the testing conditions, the soft-EHL equations for determining film thickness were found to be most appropriate [11]. These soft-EHL equations were applied to estimate the film thickness to verify the lubrication regime [12]. The equivalent modulus was assumed to be equal to the softer shoe materials, which were polyurethane and rubber (approximate elastic modulus of 10–50 MPa [13, 14]). These equations indicated that the film thickness was much less than the RMS roughness for all conditions, thus confirming the boundary lubrication assumption.

### 2.3 Data Analysis

The contributions of adhesion and hysteresis to the overall dry friction were quantified by considering both dry conditions and conditions where an excellent boundary lubricant was assumed to block all adhesion. This method has been used to isolate the relative contributions of adhesion and ploughing during metal friction [15, 16]. The dry friction force ($FF$) was assumed to include friction due to the adhesion and hysteresis contributions, Eq. (1).

$$FF_{\text{dry}} = FF_{\text{adhesion}} + FF_{\text{hysteresis}} \tag{1}$$

The lubricant, SAE 75W-140 gear oil (376.5 cP), was used to block most of the adhesion and to isolate the friction due to hysteresis [17]. The difference between the dry and SAE 75W-140 lubricated, $FF_{\text{SAE 75W-140}}$, friction represents the friction due to adhesion, Eq. (3) [17].

$$FF_{\text{hysteresis}} = FF_{\text{SAE75W}-140} \tag{2}$$

$$FF_{\text{adhesion}} = FF_{\text{dry}} - FF_{\text{hysteresis}} \tag{3}$$

The amount of boundary lubrication adhesion in the presence of fluid contaminants was then quantified. The friction force due to adhesion was calculated for each lubricant by subtracting the hysteresis friction (Eq. 4) from the friction for a given lubricant.

$$FF_{\text{adhesion(lubricated)}} = FF_{\text{lubricated}} - FF_{\text{hysteresis}} \tag{4}$$

### 2.4 Statistical Analysis

Statistical analyses were performed to identify significant effects of shoe material and flooring on dry adhesion and hysteresis friction and to identify significant effects of shoe material, flooring and fluid on the lubricated adhesion. An ANOVA analysis was conducted with $FF_{\text{adhesion}}$ and $FF_{\text{hysteresis}}$ as the dependent variables and shoe material and flooring as the independent variables. The lubricated friction due to adhesion [$FF_{\text{adhesion(lubricated)}}$] was analyzed using two ANOVA models. The first model was meant to determine the contributions from the shoe, flooring, and lubricant on adhesion friction. Independent variables for this analysis included the shoe material, floor material, lubricant, and all interaction effects. The second model was a simplified model to determine the predictive ability of just the fluid and dry adhesion friction based on the principle that a fluid blocks a portion but not all adhesion friction. $FF_{\text{adhesion(lubricated)}}$ was the dependent variable and the fluid, $FF_{\text{adhesion(dry)}}$ and their interaction were the independent variables. If these variables were found to be statistically significant, a regression model using the parameter estimates would be generated [Eq. (5)] with $\alpha$ and $\beta$ as fluid properties and $FF_{\text{adhesion(dry)}}$ being a property of the combined shoe and floor combination. The fluid parameter, $\alpha$, represents how much adhesion friction the fluid has while the parameter, $\beta$, represents the dependence of the adhesion friction on the dry friction.

$$FF_{\text{adhesion(lubricated)}} = \alpha + \beta \times FF_{\text{adhesion(dry)}} \tag{5}$$

## 3 Results and Discussion

### 3.1 Dry Adhesion

Dry adhesion friction was significantly affected by the shoe material and shoe material-flooring interaction ($p < 0.01$). For both flooring conditions, adhesion was the highest with the hardest rubber shoe material and lowest for the relatively soft polyurethane shoe material (Fig. 3). The marble flooring was found to have higher adhesion than the vinyl flooring with the hard rubber shoe surface but this effect was reversed for the soft rubber and polyurethane shoe materials.

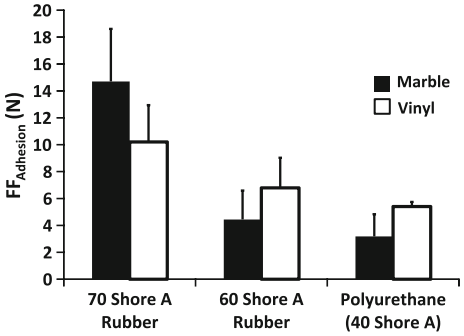


**Fig. 3** Change in adhesion friction ($FF_{\text{adhesion}}$) with respect to varying shoe and floor materials

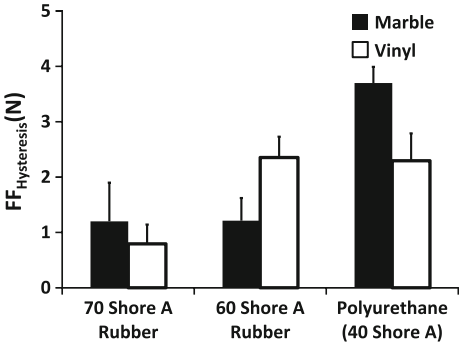


**Fig. 4** Change in hysteresis friction ($FF_{\text{hysteresis}}$) with respect to varying shoe and floor materials

The result that harder materials resulted in higher adhesion friction initially seems to contradict adhesion theory. Typically, softer and more compliant materials are associated with higher adhesion due to an increase in the real area of contact between materials [18]. The results of this study, however, may be explained by the inverse relationship between shoe hardness and roughness (Table 1). Material properties and roughness are both contributing factors to the real area of contact [19]. Thus, the low roughness of the hard material may have actually resulted in a higher real area of contact than the soft but high roughness polyurethane. Another explanation for this effect may be that the hard material formed stronger adhesional junctions with the floor surface that may have required higher shear forces to break due to an increased level of fracture toughness [20].

### 3.2 Hysteresis

Hysteresis friction was found to be affected by both the shoe and the floor materials (Fig. 4). Hysteresis friction tended to be the highest for the softest material and lowest for the hardest material. In addition, the greatest hysteresis occurred when the hard marble was combined with the soft polyurethane while the smallest hysteresis was found when the hard rubber was combined with the softer floor material, vinyl. These results are consistent with hysteresis theory that states hysteresis friction is proportional to the penetration depth of the hard asperity into the softer elastomer [21]. A softer shoe material would allow the floor asperities to achieve greater penetration depth.

### 3.3 Effect of Lubricants on Adhesion

The $FF_{\text{adhesion}}$ was found to be significantly affected by shoe material ($p < 0.001$), lubricant ($p < 0.001$), shoe–floor interaction ($p < 0.05$), shoe-lubricant interaction ($p < 0.001$), and floor-lubricant interaction ($p < 0.001$). Adhesion in the presence of a fluid, therefore, is a complex and multifactorial parameter that is influenced by the shoe material, floor material and fluid. For the case of polyurethane, the amount of adhesion was the highest for the water, followed by a statistical tie between the 25 % and 50 % diluted glycerol, then detergent and 75 % glycerol and then canola oil (Fig. 5). The soft rubber shoe material had, on average, more adhesion friction than the polyurethane and hard rubber, which were similar (Fig. 5). The addition of a liquid lubricant typically results in decreased surface energy and thereby decreased adhesion [18]. Adhesion was blocked least in the water and most in the high-viscous canola oil. While there were not significant differences across the different concentrations of glycerol, the boundary lubrication friction force tended to have an inverse relationship with both the viscosity of the fluid or the length of the molecules [18]. Water is composed of the shortest chain molecules and therefore only formed a small

**Table 1** Surface profile parameters for all shoe and floor samples, average of 5 measurements ± standard deviation

| Material | $R_a$ (μm) | $R_z$ (μm) | $R_p$ (μm) | $R_r$ (μm) |
|---|---|---|---|---|
| Polyurethane (40 Shore A) | 6.46 ± 0.78 | 31.32 ± 4.95 | 16.74 ± 3.00 | 36.22 ± 6.60 |
| Rubber (60 Shore A) | 5.23 ± 0.50 | 29.26 ± 2.59 | 13.66 ± 1.11 | 35.10 ± 4.95 |
| Rubber (70 Shore A) | 3.39 ± 0.38 | 19.98 ± 2.77 | 8.94 ± 1.09 | 23.98 ± 4.46 |
| Vinyl (99 Shore A) | 1.89 ± 0.19 | 12.42 ± 2.00 | 4.92 ± 0.66 | 30.54 ± 9.84 |
| Marble (>100 Shore A) | 0.17 ± 0.05 | 1.86 ± 0.48 | 0.40 ± 0.25 | 11.50 ± 3.18 |

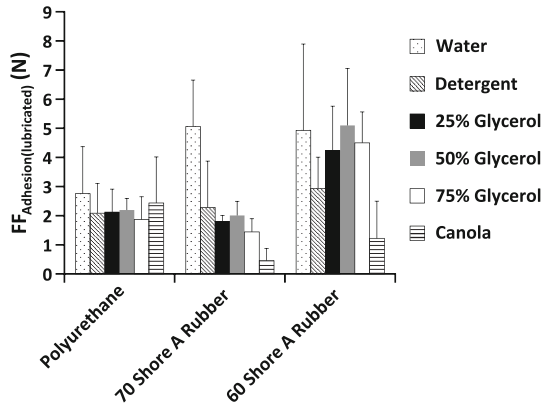


**Fig. 5** Adhesion friction force [$FF_{\text{adhesion(lubricated)}}$] with respect to varying lubricants and shoe materials

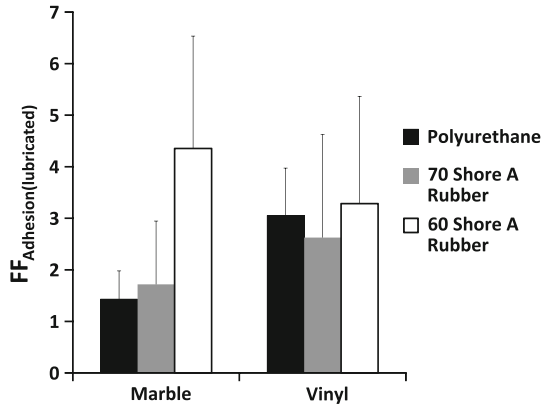


**Fig. 6** Adhesion friction force [$FF_{\text{adhesion(lubricated)}}$] across the different shoe and floor surfaces

monolayer, whereas canola oil is composed of the longest chain molecules and therefore was able to block more adhesion by generating a larger monolayer.

Further exploration of the lubricant-shoe material interaction revealed that the friction variation across the fluids was just 0.89 N (range from 1.87 to 2.76 N) for polyurethane shoe material but was 4.61 N (range from 0.45 to 5.06 N) and 3.88 N (1.25 to 5.02 N) for the hard rubber and soft rubber, respectively (Fig. 5). The shoe-lubricant effect may be explained by elastomer tribology theory that has examined the friction and wear of elastomers in the presence of fluids. Polyurethane materials have been shown to resist polishing [22], have a higher friction coefficient in the presence of oil contaminants [23] and wear at a slower rate than rubber during sliding in the presence of a fluid [24]. Therefore, rubber is more prone to react with lubricants during sliding. This may explain why the variation in frictional force across the different fluids was so much higher for rubber than it was for the polyurethane material. These results identify that some shoe

**Table 2** Parameter estimates ($\alpha$ and $\beta$) for predicting lubricated adhesion

| Fluid | $\alpha$ ($N$) | $\beta$ |
|---|---|---|
| Water | 4.3263 | 0.0531 |
| 1.5 % Detergent | 2.6125 | 0.0399 |
| 25 % Glycerol | 2.5707 | 0.0822 |
| 50 % Glycerol | 2.8006 | 0.1027 |
| 75 % Glycerol | 2.3826 | 0.0927 |
| Canola oil | 1.7556 | 0.0106 |

materials (i.e., polyurethane) have adhesion friction that is largely independent of the fluid that is present. This may provide guidance to identify the best shoes for resisting low boundary lubrication friction in environments where excellent lubricants (i.e., oils) are found.

Further exploration of the shoe–floor interaction indicated that the vinyl flooring had more friction than the marble flooring although this relationship was reversed when tested against the soft rubber shoe material (Fig. 6). The floor-lubricant interaction was driven by the lower marble adhesion friction than vinyl adhesion friction for all fluids except the low-concentration glycerol fluids. The $R^2$ of the ANOVA model considering shoe, flooring, lubricant and the first-order interactions was 0.66 indicating that 66 % of the friction variation could be explained by considering the primary and first interaction effects.

The second model (Eq. 5) revealed that the lubricant ($p < 0.001$), dry adhesion friction ($p < 0.001$), and their interaction ($p < 0.01$) were statistically significant. This model had an $R^2$ of 0.49 indicating that fluid and dry adhesion friction alone were capable of predicting 49 % of the total adhesion friction. The $\alpha$ fluid estimate, which indicates adhesion friction independent of the shoe–floor combination, was found to be highest for water, lowest for canola oil and similar for detergent and glycerol combinations. The $\beta$ parameter, which indicates the dependence of lubricated adhesion friction on dry adhesion friction, was found to be the highest among the glycerol fluids, moderate for the water and detergent contaminants, and low for the canola oil contaminant (Table 2). Therefore, some fluids (i.e., water) have high adhesion friction but are not strongly linked with the dry adhesion friction, while the glycerol contaminants have lower adhesion friction intercept but the lubricated adhesion has strong dependence on dry adhesion friction. Canola oil has low adhesion friction and the lubricated adhesion has a low dependence on the dry adhesion. The average error between the predicted values and the actual friction values was 1.05 N, which was only slightly higher than the average standard deviation for each shoe–floor-fluid combination (0.82 N). These experimental results demonstrate that the potential for an

adhesion friction model, which is based on just two fluid parameters and the dry adhesion friction, to predict lubricated adhesion friction. This regression model may be incorporated to improve existing shoe–floor-contaminant friction models that have considered the hydrodynamics between shoe and floor materials but have not considered the boundary lubrication effects [9].

### 3.4 Limitations/Assumptions

1. This study only considered a single normal load and sliding speed. Coefficient of friction for shoe and floor materials has been shown to have some dependence on the normal force [25]. Therefore, the friction values and the trends observed in this study may vary with normal force. The adhesion friction regression equation also may have minimal relevance as the normal loading approaches 0 [26]. The normal force was selected so that it resulted in contact pressures similar to walking (See Sect. 3.2), to ensure relevance to human slipping events. In addition, sliding speeds were relatively low (0.01 m $s^{-1}$) compared to slipping events (up to 1 m) [27] to isolate the effects of boundary lubrication. Slipping events occurring at higher speeds may include hydrodynamic effects due to the wedge term [9, 25]. Friction measurements were conducted at steady state, which may ignore transitional squeeze-film effects [28].
2. While adhesion was assumed to be mostly blocked by SAE 75W-140 oil, it is likely that a very small amount of adhesion could have still occurred at the interface, which was included in the hysteresis portion of friction.
3. Experiments were conducted using a pin-on-disk apparatus, which did not include many of the dynamic effects of slipping or the hydrodynamic effects in the shoe–floor surface during slipping. These results, however, are expected to be relevant to slips that occur in the absence of hydrodynamic effects. The fact that boundary lubrication friction forces were frequently under 20 % of the normal load (i.e., under an available coefficient of friction value of 0.20) threshold needed to support ambulation [3] indicates that slips may occur in the absence of hydrodynamic effects.

### 3.5 Future Work

While the results of this research will contribute to furthering the current understanding of what causes shoe–floor contacts to be slippery, the results need to be incorporated as part of a larger analysis which incorporates fluid pressure effects for a whole shoe design to be directly applicable to a slip and fall accident. In addition, creating predictive models, which simulate both the boundary lubrication and hydrodynamic effects, would have tremendous utility in designing slip-resistant workplaces and preventing falling accidents.

## 4 Conclusions

Important conclusions related to shoe–floor-contaminant interactions were made based on this study:

1. The hysteresis contribution to friction is significantly affected by the ratio of shoe hardness to floor hardness.
2. The smoothest shoe material, while also being the hardest, resulted in the greatest adhesional contribution to friction under dry conditions. The roughest material, while also being the softest, resulted in the lowest adhesional contributions under dry conditions.
3. Polyurethane is able to maintain adhesion under lubricated conditions better than the rubber shoe materials. The rubber shoe material was most susceptible to the decreasing adhesion when lubricated.
4. Lubricants composed of molecules with longer chain lengths resulted in decreased adhesion.
5. A regression model including two fluid parameters and the dry adhesion was effective at predicting lubricated adhesion.

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