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## ANALYSIS OF THE CONTRIBUTION OF ADHESION AND PLOUGHING TO SHOE-FLOOR LUBRICATED FRICTION IN THE BOUNDARY LUBRICATION REGIME

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### ABSTRACT

Slip and fall accidents cost billions of dollars each year. Shoe-floor-lubricant friction has been shown to follow the Stribeck effect, operating primarily in the boundary and mixed-lubrication regimes. Two of the most important factors believed to significantly contribute to shoe-floor-lubricant friction in the boundary lubrication regime are adhesion and ploughing. Experiments were conducted using a pin-on-disk tribometer to quantify adhesion and ploughing contributions to shoe-floor friction in dry and lubricated conditions. The coefficient of friction between three shoe materials and two floor materials of different hardness and roughness were considered. Experiments were conducted under six lubricants for a sliding speed of 0.01 m/sec at ambient conditions. It was found that the contribution of adhesion and ploughing to shoe-floor-lubricant friction was significantly affected by material hardness, roughness, and lubricant properties. Material hardness and roughness are known to affect adhesion, with increased hardness or increased roughness typically resulting in decreased adhesion. The smoothest shoe material, while also being the hardest, resulted in the greatest adhesional contribution to friction. The roughest material, while also being the softest, resulted in the lowest adhesional contributions under dry conditions. Canola oil consistently resulted in the lowest percent of full adhesion and water consistently resulted in the highest percent of full adhesion, presumably due to the thickness of the boundary lubrication layer. Ploughing contribution was dependent upon the hardness of the shoe and floor materials. A positive correlation was found between the shoe and floor hardness ratio and ploughing coefficient of friction.

### NOMENCLATURE

COF<sub>adhesion</sub> – contribution of adhesion to coefficient of friction  
 COF<sub>plough</sub> – contribution of ploughing to coefficient of friction  
 COF<sub>adhesion+plough</sub> – coefficient of friction including both adhesional and ploughing contributions  
 COF<sub>lubricated</sub> – lubricated coefficient of friction

%COF<sub>adhesion</sub> – percentage of coefficient of adhesion available

$\tilde{H}_{e,min}$  – nondimensional film thickness;  $\tilde{H}_{e,min} = \frac{\tilde{h}_{min}}{R'}$

$\tilde{h}_{min}$  [m] – minimum film thickness

$R'$  [m] – reduced radius of curvature

$U$  – nondimensional speed parameter;  $U = \frac{\eta v}{E' R'}$

$v$  [m/sec] – velocity

$\eta$  [Pa s] – viscosity

$E'$  [N/m<sup>2</sup>] – effective elastic modulus

$W$  – nondimensional load parameter;  $W = \frac{w}{E' R'}$

$w$  [N] – normal load

$k$  – ellipticity parameter

$\lambda$  – ratio of film thickness to roughness

### INTRODUCTION

Slip and fall accidents cost approximately \$13.9 billion in 2007 in the United States [1]. Typically a slip occurs when the coefficient of friction required for gait, which generally ranges between 0.17 and 0.22 [2], is greater than the coefficient of friction available between the shoe and floor. Understanding the mechanisms which govern shoe-floor-lubricant friction is essential to 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 [3]. Previous work by one of the current authors [3] has addressed 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 not received much attention. Yet even under boundary lubrication conditions, shoe-floor-lubricant coefficient of friction is often below the friction required for walking [4]. Bowden and Tabor's classical work established that adhesion and ploughing are the primary sources of friction in the absence of hydrodynamic effects [5]. Adhesion is affected by the real area

of contact (i.e. due to elastic modulus, hardness, and roughness parameters) and lubrication [6]. Menezes et al. [7] applied comparisons between unlubricated and mineral oil lubricated conditions to determine the relative contributions of adhesion and ploughing to the total overall friction. The purpose of the presented research is to examine the contribution of adhesion and ploughing to shoe-floor friction under varying lubricants.

## METHODS

Experiments were conducted using a custom developed pin-on-disk type tribometer. All tests were carried out under a constant normal load of 20.9 N in ambient conditions, resulting in a biofidelic contact pressure of 266.1 kPa at a single sliding speed of 0.01 m/sec.

Three circular, 10 mm diameter, unthreaded shoe materials, polyurethane (40 shore A hardness), rubber (60 shore A hardness), and another rubber (70 shore A hardness) were examined. Shoe materials were conditioned with 220 grit sandpaper before each experiment to ensure consistent roughness. Commercially available vinyl tile (99 shore A hardness) and marble tile (>>100 shore A hardness) disks were tested. All floor materials had dimensions of 304.8 mm x 304.8 mm x 35 mm. A durometer was used to measure the hardness of each shoe and floor sample on a shore A scale of 1 to 100. A 2D contact stylus profilometer was used to measure surface roughness parameters of all materials and the average values of five measurements are presented in Table 1. In table 1,  $R_a$  is the arithmetic mean of the surface profile,  $R_z$  is the maximum peak to valley height,  $R_p$  is the maximum profile peak height and  $R_t$  is the total height of profile.

Table 1. Roughness parameters for all shoe and floor samples

Materials	$R_a$ [μm]	$R_z$ [μm]	$R_p$ [μm]	$R_t$ [μm]
Rubber (70shoreA)	3.39	19.98	8.94	23.98
Rubber (60shoreA)	5.23	29.26	13.66	35.10
PU (40shoreA)	6.46	31.32	16.74	36.22
Vinyl (99shoreA)	1.89	12.42	4.92	30.54
Marble (>100shoreA)	0.17	1.86	0.40	11.50

The shoe-floor combinations were tested under dry and lubricated conditions where 250 mL of fluid was applied for lubricated experiments resulting in a fluid thickness of approximately 0.26 cm.

The examined shoe-floor-lubricant contacts were identified to operate under soft-EHL contact [8]. The lubrication regime was determined by calculating the parameter ' $\lambda$ ' (Eq. (1)) [9] which is the ratio of the film thickness to roughness where  $\lambda < 1$  coincides with boundary lubricated contact. The non-dimensional film thickness under soft-EHL is calculated from Eq. (2) [9]. Based on the analysis, the present experiments were predicted to operate in boundary lubrication.

$$\lambda = \frac{\bar{H}_{e,min} * R'}{\sigma'} \quad (1)$$

$$\bar{H}_{e,min} = 7.43U^{0.65}W^{-0.21}(1 - 0.85e^{-0.31k}) \quad (2)$$

The contributions of adhesion and ploughing were determined by comparing COF values of lubricated and dry conditions. Dry coefficient of friction was assumed to include friction due to the maximum possible adhesion and ploughing effects. A lubricant, SAE 75W-140 gear oil (376.5 cP), was selected that would minimize most adhesion similar to methods proposed by Menezes et al. [7]. The difference between the dry and SAE 75W-140 lubricated coefficient of friction represents the coefficient of friction due to only adhesion, Eq. (3) [7].

$$COF_{adhesion} = COF_{adhesion+plough} - COF_{plough} \quad (3)$$

The coefficient of friction obtained for water (0.52 cP), 1.5% detergent (1.8 cP), 25% glycerol-75% water (1.9 cP), 50% glycerol-50% water (5.54 cP), 75% glycerol-25% water (41 cP), and canola oil (74.6 cP) was categorized by the percent contribution of adhesion to friction, Eq.(4). The %COF<sub>adhesion</sub> under each shoe-floor-lubricant combination is indicative of how much each lubricant allows shoe-floor adhesion.

$$\%COF_{adhesion} = \frac{COF_{lubricated} - COF_{plough}}{COF_{adhesion}} * 100\% \quad (4)$$

The percent of full adhesion available under varying lubricants, %COF<sub>adhesion</sub>, is calculated as the ratio between the coefficient of friction due to adhesion under lubricated and dry conditions.

Under all conditions, the COF<sub>adhesion</sub>, COF<sub>plough</sub>, and %COF<sub>adhesion</sub> was averaged over five trials. An ANOVA was performed to determine the statistical significance of varying shoe, floor, and lubricants on %COF<sub>adhesion</sub>,  $p < 0.05$ .

## RESULTS AND DISCUSSION

The calculated COF<sub>adhesion</sub> and COF<sub>plough</sub> of each shoe and floor combination are listed in Table 2. Experiments conducted with 70 shore A hardness rubber resulted in the greatest adhesion and the lowest ploughing contributions, whereas polyurethane resulted in the lowest adhesion contributions. While harder materials typically result in a decrease in the real area of contact and thereby decreased adhesion [6], the reduction in roughness (Table 1) that accompanied the hardest material may have led to an overall reduction in contact area and reduced adhesion. Increased roughness results in a decrease in real contact area [6], therefore the roughest material (polyurethane) while being the softest and most ductile material resulted in the lowest COF<sub>adhesion</sub>. These results suggest that roughness seems to be more dominant than shoe hardness in its contribution to shoe-floor adhesion.

Table 2. Collected COF<sub>adhesion</sub> and COF<sub>plough</sub>

	VINYL		MARBLE	
	COF <sub>adhesion</sub>	COF <sub>plough</sub>	COF <sub>adhesion</sub>	COF <sub>plough</sub>
Rubber (70ShoreA)	0.48±0.13	0.04±0.02	0.70±0.19	0.06±0.03
Rubber (60ShoreA)	0.33 ±0.11	0.11±0.02	0.21±0.10	0.06±0.02
PU (40shoreA)	0.26±0.02	0.11±0.02	0.15±0.08	0.18±0.01

Shoe and floor materials significantly affected the ploughing contribution to friction. Ploughing occurs at soft and hard material contacts where harder asperities are able to penetrate softer material asperities and plough the material [6]. Under all conditions floor materials were harder than shoe materials. As the difference between shoe and floor hardness increased, ploughing was observed to increase. The experiments conducted with the softest shoe material (polyurethane) and the hardest floor material (marble) resulted in an average  $COF_{plough}$  of 0.18. Experiments conducted to examine the shoe-floor combination with the smallest difference in hardness of materials, 70 shore A rubber and vinyl, resulted in the smallest average  $COF_{plough}$  of 0.04.

Figure 1. Change in  $\%COF_{adhesion}$  with respect varying lubricants and shoe materials, (a) vinyl tile and (b) marble tile

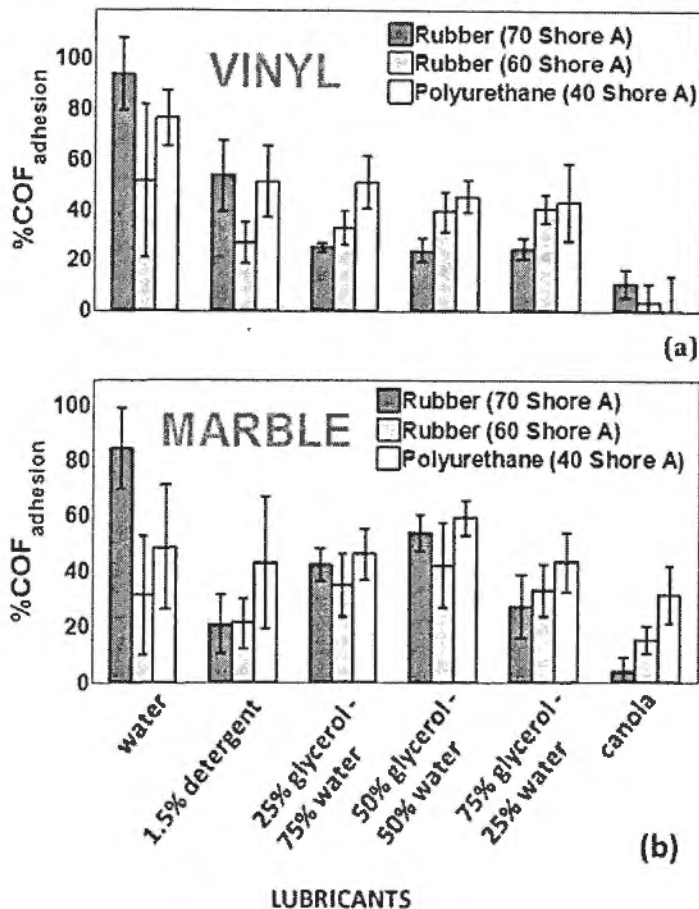


Figure 1a and Figure 1b show the change in  $\%COF_{adhesion}$  under varying shoe and lubrication conditions for vinyl and marble contact, respectively. Across all experiments, polyurethane and 70 shore A rubber resulted in significantly different average  $\%COF_{adhesion}$  of 43.9% and 38.6%, respectively. This indicates that on average across all lubricant conditions, polyurethane was not as susceptible to decrease in adhesion as 70 shore A rubber. With respect to varying lubricants, experiments conducted with canola oil lubricated contacts resulted in significantly lower average  $\%COF_{adhesion}$ , 10.7%, and experiments conducted with water lubricated

contacts when compared to other lubricants resulted in significantly higher average  $\%COF_{adhesion}$ , 61.4%. The best boundary lubricants are long chain polar molecules [6]. Water is composed of the shortest chain molecules, whereas canola oil is composed of the longest chain molecules. Therefore, a monolayer of canola blocked adhesional affects better than the other lubricants examined.

## CONCLUSIONS

1. The ploughing 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. Softer shoe materials are able to maintain adhesion under lubricated conditions better than harder shoe materials. The hardest shoe material was most susceptible to decreasing adhesion when lubricated.
4. Lubricants composed of molecules with longer chain lengths resulted in decreased adhesion.

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