MULTISCALE COMPUTATIONAL MODELING OF SHOE-FLOOR FRICTION

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INTRODUCTION

Slip and fall accidents present a major health and occupational hazard. Increased shoe-floor coefficient of friction (COF) has been demonstrated to be indicative of reduced slipping risk [1].

Previous research by our group has shown that a microscopic finite element model can predict COF of shoe-floor samples by considering roughness and material properties [2]. However, that study did not consider macroscopic interactions and few other studies have attempted to model whole-shoe friction against walkway surfaces [3]. Current study builds on previous research by expanding the model to consider macroscopic (i.e., whole-shoe) interactions with the floor surface. As a first step towards a comprehensive shoe-floor-contaminant COF model, this study focuses on hysteresis friction, since it is the dominant friction mechanism on lubricated shoe-floor surfaces [2].

METHODS

The model consists of a microscopic model that simulates the interaction between shoe and floor asperities and a macroscopic model that determines contact pressure across the shoe surface. The microscopic model yields hysteresis COF as a function of contact pressure and macroscopic model uses this relationship and the predicted contact pressure to calculate the overall COF.

The microscopic model consists of a rough shoe material sliding against a rigid floor surface (Figure 1 (Left)) [2]. The asperity heights of these blocks were set to achieve a desired peak to valley roughness (R_z) and spacing between asperities was selected to achieve a desired average slope (Δ_a). Shoe material was modeled as a viscoelastic material, which causes energy loss as shoe

asperities deform and relax, while sliding over floor asperities. The hysteresis COF for micro-model was determined as the ratio of shear to normal force. Three different shoe materials were simulated against a single floor surface. Surface parameters were measured and averaged across four scans using a two dimensional stylus profilometer (Taylor-Hobson Surtronic S100 ®, Leicester, UK) (Scan length: 6.2 mm; low-pass cutoff filter: 0.8 mm). The boots had a consistent roughness (R_z = 24.5 µm, Δ_a = 29°) across the three materials. The flooring's roughness was also recorded and applied to the model (R_z = 9.5 µm, Δ_a = 24°). Shore A Hardness of the three boots was measured and used to characterize material properties of the three boots i.e. short-time shear modulus, G_0, long-time shear modulus, G_∞, and decay constant, β, using relationships introduced in [4] (Table 1). Microscopic simulation was repeated over several contact pressures to produce an exponential fit model between contact pressure and COF.

Material geometry for macro-model was determined using 3D scan of a shoe (Faro ScanArm ®) (Figure 1(Right)). Contact simulations were performed using explicit analysis (LS-Dyna, LSTC, Livermore, CA, USA). Vertical displacement of the shoe was applied until reaching a normal force level of 250 N, while the sliding velocity was 0.3 m/s and shoe-floor angle was 7°. Shoe material was modeled as linear elastic for computational efficiency since viscoelastic contributions to hysteresis friction were already accounted for in microscopic model (Table 1).

Figure 1. Micro (Left) and macro- model (Right)

Table 1. Material parameters used for boots

Shore A	G_0(MPa)	G_∞(MPa)	β (s^{-1})	E(MPa)
85	4.39	1.84	0.022	13.18
76	2.48	0.99	0.017	7.44
64	1.41	0.92	0.2	4.24

Friction force was calculated based on the contact pressure (p_i) and area (A_i) for each element from the macro-model, and the COF values as a function of contact pressures $(COF_{(p_i)})$ from the micro-model (Eq.1). COF was calculated as the ratio of average friction force to normal force (Eq. 2).

$$F_{Friction}= \Sigma\ COF(p_i)* p_i* A_i \qquad Eq.\ 1.$$

$$COF=F_{Friction}/ F_{Normal} \qquad Eq.\ 2.$$

RESULTS AND DISCUSSION

An exponential fit described the relationship between predicted COF and contact pressure with an R^2 of greater than 0.93 for all three materials (Figure 2). The micro-model revealed that the hardest material experienced the greatest level of hysteresis COF and the medium and low hardness material had similar but less hysteresis COF.
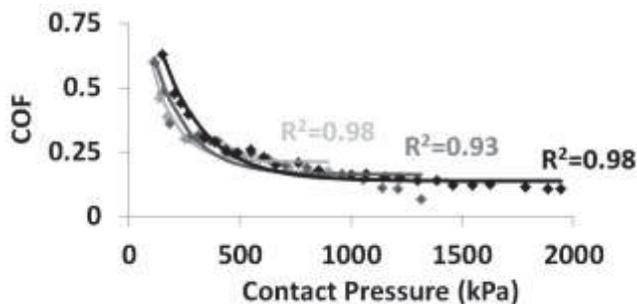

Figure 2. Curve fitting for materials. Hardness: Low(Light Gray), Medium(Gray) and High(Black).

The macro-model revealed that pressures were typically along the posterior portion of the shoe. Increasing shoe hardness was found to increase average and peak pressures and reduce contact area (Figure 3.). Increased contact pressures of the hard shoe led to an overall reduction of hysteresis COF (Figure 4.). This finding was consistent with experimental measurements of shoe-floor COF (Figure 4.) and with slipping risk during unexpected human slips [5]. The model did overestimate hysteresis COF since it predicted COF values

between 0.25 and 0.3 whereas experiments found COF values between 0.15 and 0.2. This discrepancy may be due to the fact that the floor was modeled as rigid, which may have overestimated the hysteresis COF between the floor asperities and the shoe material. Overall, this study demonstrates the potential for using finite element analysis to model shoe-floor friction in a way that predicts slipping risk. The model suggests that the mechanism behind increased COF for soft shoe material is increased contact area and reduced contact pressures.
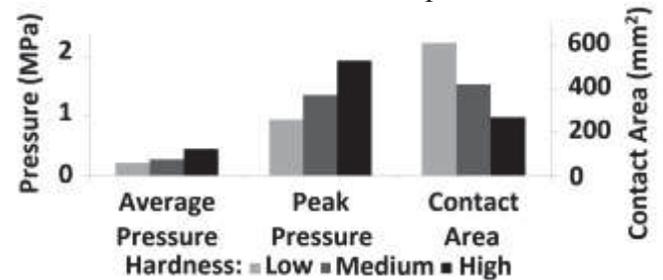

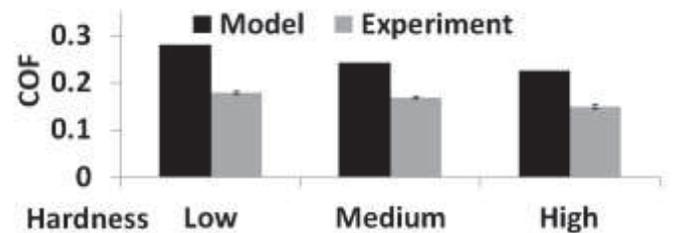**Figure 3.** Contact pressure and contact area across the three materials.

Figure 4. COF obtained from model versus experiments.

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