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USING A 3-DIMENSIONAL VISCOELASTIC FINITE ELEMENT MODEL TO ANALYZE THE EFFECTS OF FLOOR ROUGHNESS, SLIDING SPEED AND MATERIAL PROPERTIES ON SHOE-FLOOR FRICTION

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ABSTRACT

Slip and fall accidents are a major occupational health concern. Important factors affecting shoe-floor friction is critical to identifying and resolving unsafe surfaces and designing. Experimental studies have indicated that several factors including floor roughness, sliding speed and shoe materials affect shoe-floor friction although the precise nature of the mechanism behind this phenomenon is not well understood. In addition, recent studies have suggested that boundary lubrication is highly relevant to slipping and that adhesion and hysteresis are the main contributing factors to boundary lubrication. The purpose of this study is to perform the numerical simulations to analyze the effects of floor roughness (asperity height), sliding speed and material properties on ratio of real area of contact and normal force (relevant to adhesion friction) and hysteresis friction for a viscoelastic shoe material interacting with a hard floor surface. A 3D shoe model and 3D vinyl floor model was simulated with speed 0.01 m/s, 0.5 m/s, 0.75 m/s and 1 m/s in three different floor surfaces. The material property was also varied in the numerical simulations. The study showed that roughness affects both the hysteresis and adhesion friction whereas sliding speed and material property affects the adhesion friction only. The dependence of adhesion and hysteresis friction on roughness, sliding speed and material property is useful in understanding the shoe-floor friction phenomenon and development of slip resistant sports and work shoes.

INTRODUCTION

Fourteen percent of the total fatal occupational injuries are the slip and fall related and counts as a second most fatal work related injury in 2009 [1]. Shoe-floor friction is an important contributing factor to the slip and fall events. Recent studies by our research group [2] identified that boundary lubrication is highly relevant to slipping. In boundary lubrication, the viscoelastic rubber materials typically are deformed by the floor asperities causing hysteresis friction and junctions are formed between the shoe and floor materials causing adhesion.

Adhesion and hysteresis friction are important contributors to the available coefficient of friction between shoe and floor materials [3]. In the real area of contact region, the two surfaces are loaded together and their asperity tips forms an adhesional bond, which requires shear force to break. Contact area, which is a function of the asperity geometry, roughness, elastic modulus, and surface energy of the two materials contribute to adhesion friction. In viscoelastic materials, hysteresis occurs when energy is lost during cyclic deformation of the softer shoe material by the hard shoe asperities . Thus, it is important to understand the adhesion and hysteresis friction during the sliding motion of shoe sole over rough surface.

The objective of this study is to simulate the interaction of shoe and floor asperities using finite element analysis while varying floor roughness, shoe sole speed, and shoe sole material property. Specifically, the friction force due to hysteresis and adhesion friction will be analyzed. A 3D computational model of shoe sole sliding motion over a piece of floor material with micro-level asperities will be conducted using explicit analyses.

METHODS

Finite Element Model

Numerical simulations were carried out using explicit finite element code, LS-DYNA, due to the high deformation that was expected in the viscoelastic shoe material (. Rough shoe (1 mm x 0.5 mm x 0.5 mm) and floor (2 mm x 1 mm x 0.135 mm) samples were modeled using brick elements (Figure 1) with pyramidal asperities. The frequency and approximate height of asperities across the surface (i.e. number of asperities per mm) was taken from stylus profile scans of actual shoe and floor surfaces (Table 1). Non-linear viscoelastic material model was used for the shoe sole model with two different polyurethane material properties [4] (Table 2). A rigid material model was applied to the floor with the assumption that floor was much harder than the shoe material. Because the shoe material was non-linear, a non-linear surface to surface contact analysis was performed with the input friction value set at 0. The shear friction was set to 0 so that the hysteresis friction came only from the deformation of the materials and not from the contact algorithm. Boundary constraints were applied to the floor model so that it was completely fixed. The shoe sole was given boundary conditions such that its top surface moved downward until resulting in a normal force of 0.25 N/mm^2 for the first 1.2 m/s of the simulation and then a horizontal direction for the next 1.8 m/s of the simulation.

Table 1 Material roughness parameter for polyurethane and vinyl floor

Materials	Peak Count (R_{pc})
Polyurethane	6.25 (~ 6) per mm length
Vinyl floor	3.91(~ 4) per mm length

Table 2 Material properties of two different polyurethane material model

Material model	Bulk Modulus (Nmm^{-2})	Short time shear modulus (Nmm^{-2})	Long time shear modulus (Nmm^{-2})	Decay constant (s^{-1})
Polyurethane material model 1	417	103	4.69	68000
Polyurethane material model 2	417	241	15.2	68000

Simulations were performed for 4 different sliding speeds 0.01 ms^{-1}, 0.5 ms^{-1}, 0.75 ms^{-1} and 1 ms^{-1} and three different asperity flooring height of 5 μm, 7.5 μm and 10 μm. Two different viscoelastic materials with different short and long shear modulus were also used (Table 1).

Analysis

Hysteresis coefficient of friction ($COF_{hysteresis}$) was calculated by taking the ratio of shear force and normal force (Eq.1).

$$COF_{Hysteresis} = \frac{F_{shear}}{F_{Normal}} \quad (1)$$

Adhesion frictional force depends on the real area of contact [5]. The coefficient of friction due to adhesion ($COF_{adhesion}$) is the ratio of adhesion friction force and the normal force as shown by Heinrich and Kluppel for the rubber [6] in eq. 2.

$$F_{Adhesion} \propto \text{Real Area of Contact} \quad (2)$$

$$COF_{Adhesion} = \frac{F_{Adhesion}}{F_{Normal}} \quad (3)$$

$$COF_{Adhesion} \propto \frac{\text{Real Area of Contact}}{F_{Normal}} \quad (4)$$

From the Eq. 2-4, we get $COF_{adhesion}$ proportional to the ratio of real area of contact and normal force.

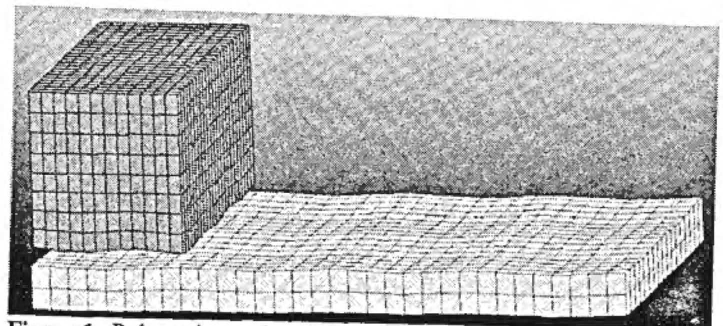

Figure.1. Polyurethane shoe sole model and vinyl floor model with asperities on the floor surface build in LS-DYNA

RESULTS AND DISCUSSION

When the asperities height of floor model is varied from 5 μm to 10 μm, $COF_{hysteresis}$ is increased whereas ratio of real area of contact to normal force (adhesion friction) is decreased as shown in Table 3. The increase in hysteresis friction is due to increased stress development in viscoelastic sample from the higher asperities, which causes energy loss as explained by Bui and Ponthot [7]. The decrease in real area of contact indicates that the polyurethane model asperities are not able to penetrate the floor asperities. The decreased contact area with increasing asperity height is consistent with theory by Bhushan [8]who stated an inverse relationship between roughness and real area of contact.

Table. 3. Variation $COF_{hysteresis}$ and ratio of real area of contact (adhesion friction) with different asperity height of floor model

	Asperity (5 μm)	**Asperity (7.5 μm)**	**Asperity (10 μm)**
$COF_{hysteresis}$	0.039	0.058	0.075
Ratio of real area of contact (mm^2) and normal force (N)	0.21	0.15	0.12

When the speed of the polyurethane model is varied from 0.01 ms^{-1} to 1.0 ms^{-1}, $COF_{adhesion}$ is decreased and the hysteresis remains nearly constant (Table 4). As the sliding speed increases, the soft material may not able to get enough time to settle into the asperities of the harder material resulting in a loss of contact area. Experimental results from other studies also support a decrease in friction for shoe and floor materials in the range of 0-1 m/s although they described that the effect may have been due to mixed-lubrication [9]. A loss in real area of contact may also contribute to the inverse relationship between sliding speed and coefficient of friction.

Table. 4. Variation $COF_{hysteresis}$ and ratio of real area of contact (adhesion friction) with different asperity height of floor model

	Speed (0.01 m/s)	**Speed (0.5 m/s)**	**Speed (0.75 m/s)**	**Speed (1 m/s)**
COFhysteresis	0.046	0.036	0.039	0.038
Ratio of real area of contact (mm^2) and normal force (N)	0.98	0.24	0.21	0.14

When the material property of polyurethane model is changed from polyurethane material model 1 to material model 2, short time and long time shear modulus is increased and this is contributed to the increase in ratio of real area of contact (measure of adhesion friction). However, the $COF_{hysteresis}$ remain almost constant (Table 5). The possible reason for the reduction in ratio of real area of contact to normal force maybe the increase in rigidity of material due to increase in shear modulus. Bhushan [9] also stated that an increase in modulus of elasticity decreases the real area of contact[8].

Table 5. Variation $COF_{hysteresis}$ and ratio of real area of contact (adhesion friction) with different material model of polyurethane model

	Polyurethane material 1	**Polyurethane material 2**
COFhysteresis	0.058	0.056
Ratio of real area of contact (mm^2) and normal force (N)	0.15	0.12

CONCLUSIONS

The study showed that increase in roughness, sliding speed and material property (i.e. increase in shear modulus) decreases the ratio of real area of contact (measure of adhesion friction). Also, an increase in roughness led to an increases the hysteresis friction coefficient which was not affected by the sliding speed, and material property during the simulation. Therefore roughness is an important factor affecting both hysteresis and adhesion components of the friction. This model may provide valuable insights into the interaction of shoe and floor materials at a microscopic level. Future studies may wish to perform multi-scale analyses to understand how the findings of this study relate to interactions between entire shoes and floor surfaces.

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