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Predictive multiscale computational model of shoe-floor coefficient of friction original article

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ABSTRACT

Understanding the frictional interactions between the shoe and floor during walking is critical to prevention of slips and falls, particularly when contaminants are present. A multiscale finite element model of shoe-floor-contaminant friction was developed that takes into account the surface and material characteristics of the shoe and flooring in microscopic and macroscopic scales. The model calculates shoe-floor coefficient of friction (COF) in boundary lubrication regime where effects of adhesion friction and hydrodynamic pressures are negligible. The validity of model outputs was assessed by comparing model predictions to the experimental results from mechanical COF testing. The multiscale model estimates were linearly related to the experimental results ($p < 0.0001$). The model predicted 73% of variability in experimentally-measured shoe-floor-contaminant COF. The results demonstrate the potential of multiscale finite element modeling in aiding slip-resistant shoe and flooring design and reducing slip and fall injuries.

1. Introduction

Slips and falls are among the primary causes of injuries. According to the Centers for Disease Control and Prevention, falls were the leading cause of non-fatal injuries between 2001 and 2014 and are responsible for an annual financial burden of $180 billion in the United States (Florence et al., 2015a; Florence et al., 2015b). More than 50% of falls are initiated by slipping accidents in occupational settings (Courtney et al., 2001).

Frictional characteristics of the shoe-floor interface impact the likelihood of slips and falls (Beschorner et al., 2016; Burnfield and Powers, 2006; Hanson et al., 1999). The probability of slips has been predicted with the available coefficient of friction (ACOF) and the required coefficient of friction (RCOF) (Beschorner et al., 2016; Burnfield and Powers, 2006; Hanson et al., 1999; Iraqi et al., 2015). RCOF is measured during gait using force plates on dry surfaces (Chang et al., 2011). ACOF is typically measured using a mechanical device that quantifies the ratio of friction to normal forces between the shoe and flooring (Burnfield and Powers, 2006; Chang et al., 2001a; Hanson et al., 1999; Iraqi et al., 2015). Physics-based computational models of frictional behavior of the shoe-floor-lubricant complex have recently been developed to predict ACOF (Beschorner et al., 2009; Moghaddam et al., 2015). These models have advantages in that: 1. they can help explain the underlying friction mechanisms pertinent to shoe-floor friction, and 2. they can be used to predict and optimize ACOF of hypothetical shoe-floor designs (i.e., they can be used as a design tool).

Shoe-floor friction is influenced by microscopic and macroscopic features of the shoe and flooring. Relevant factors affecting ACOF on the microscopic scale include shoe and flooring surface topography, contact pressure, and outsole material properties (Beschorner et al., 2009; Moghaddam, 2013; Moghaddam et al., 2015). Relevant factors on the macroscopic scale include shoe tread design features such as geometry, tread depth, width and orientation (Blanchette and Powers, 2015; Li and Chen, 2004; Li et al., 2006), material hardness (Moghaddam and Beschorner, 2015; Tsai and Powers, 2008), sliding speed and shoe-floor contact angle (Moghaddam and Beschorner, 2016, 2017; Moyer et al., 2006). Physics-based modeling of the shoe-floor interface has the potential to elucidate how these various features contribute to friction mechanisms.

Contaminants, particularly liquids, play an important role in slipping accidents and can impact friction. Fluid can reduce ACOF by either becoming pressurized, causing a separation of the contacting surfaces (hydrodynamic lubrication) or by reducing adhesion friction without causing a separation (boundary lubrication). While some studies have utilized solely hydrodynamic theory to

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Nomenclature

A	contact area
A_{Micro}	nominal area in microscopic models
ACOF	available coefficient of friction (experimental)
COF	coefficient of friction
COF_{Model}	coefficient of friction predicted by multiscale model
Δ_q	root mean square slope of surface profiles
$F_{Friction}$	macroscopic friction force
$F_{Hysteresis}$	microscopic friction force due to hysteresis
F_{Normal}	normal load in macroscopic models
f(p)	piecewise polynomial describing frictional shear stress due to hysteresis as a function of contact pressure
G(t)	variation of shear modulus with respect to time
p	contact pressure
R_z	average peak-to-valley distance of surface profiles
σ_f	frictional shear stress due to hysteresis
τ	time constant of exponential decay in shear modulus

explain ACOF of lubricated surfaces (Beschorner et al., 2007; Li and Chen, 2004), research by our group suggests that dangerously low ACOF values can occur even without hydrodynamic effects (Cowap et al., 2015; Moghaddam et al., 2015; Moore et al., 2012; Strobel et al., 2012). Shoes with at least some tread are demonstrated to operate in boundary lubrication (Beschorner et al., 2014; Singh and Beschorner, 2014) suggesting that boundary lubrication is relevant to slipping. In boundary lubrication, hysteresis deformation of the shoe sole material is the major mechanism contributing to friction (Cowap et al., 2015; Moghaddam et al., 2015; Strobel et al., 2012). Hysteresis friction originates from viscoelastic deformation of the surface asperities (Tabor, 1974). Therefore, modeling hysteresis at the shoe-floor interface is relevant to predicting friction on liquid-contaminated surfaces.

An opportunity exists to use finite element modeling to simulate and predict shoe-floor COF. Finite element modeling has been demonstrated to be effective in modeling the impact of microscopic shoe and floor features on COF (Moghaddam et al., 2015). Furthermore, multiscale computational models have been developed for elastomers that take into account surface features in both microscopic and macroscopic levels to determine hysteresis COF (Wagner et al., 2015a; Wagner et al., 2015b). However, multiscale computational methods have not yet been applied to investigate shoe COF. This study addresses this knowledge gap by applying multiscale computational modeling techniques to actual shoe geometries to predict whole shoe-floor COF.

The purpose of this study is to develop and quantify the predictive ability of a multiscale finite element model for shoe-floor COF. The ability of the multiscale computational model as well as each of its components (microscopic and macroscopic) to predict experimental ACOF are assessed to evaluate the validity of the model. The scope of this model is boundary lubrication regime where adhesion and hydrodynamic pressure effects are negligible.

2. Methods

2.1. Multiscale model

A computational model was developed that included a microscopic and macroscopic finite element model. The microscopic model simulated the interaction between shoe and floor surface asperities to predict the frictional shear stress due to hysteresis as a function of contact pressure (Fortunato et al., 2017; Persson, 2013; Persson, 2001). The macroscopic model simulated shoe heel to floor contact to determine the contact pressure distribution across the outsole surface (Fig. 1). Contact pressure values from the macroscopic model were then combined with the microscopic model to predict the hysteresis COF. Explicit finite element software (LS-Dyna® Livermore Software Technology Corporation, Livermore, California, USA) was used for simulations.

2.1.1. Microscopic model

The microscopic model simulated contact between a rough viscoelastic shoe material and a rough rigid floor. A five-term exponentially decaying function was applied to the shoe, which described the time-dependent behavior of the shear modulus ($G(t)$) (Eq. (1)) (Moghaddam et al., 2015). Flooring was modeled as rigid because it is orders of magnitude harder than the shoe (Beschorner, 2008; Moghaddam et al., 2015). Roughness parameters including the peak-to-valley distance roughness (R_z) and root mean square slope (Δ_q), were incorporated into the models that were consistent with shoes and floors tested in the experimental measurements (See Section 2.2). Specifically, the peak-to-valley distance (R_z) was used to define the vertical distance between peak and valley nodes. Root mean square slope (Δ_q) was used to define the slope of the asperities, which affected the spacing between the asperities (Fig. 1. Left) (Moghaddam et al., 2015).

$$G(t) = \sum_{m=1}^{5} G_m e^{-t/\tau_m}, \tau_m = 10^{-(m-1)}\tau_1, \quad (1)$$

Boundary conditions for the microscopic models included: 1. constraints on the translational and the rotational degrees of freedom at the bottom surface of the floor nodes. 2. Constraints on the translational degrees of freedom were applied at the top surface of the shoe nodes. 3. Contact pressure was controlled using the vertical displacement boundary conditions that were applied at the top surface of the shoe nodes; higher contact pressures were achieved by applying more downward vertical displacement. 4. Velocity boundary conditions consistent with experiments (Section 2.2) were applied to the nodes at the top surface of the shoes. The microscopic model geometries were meshed using eight node hexahedral elements. These elements are well suited for simulating extreme deformations of soft materials (Erhart, 2011).

2.1.2. Macroscopic model

Macroscopic models were either created based on non-contact 3D laser scans (FaroArm®, Faro Technologies, Lake Mary, Florida, USA) of the shoes or CAD models developed based on the measured shoe geometries (ANSYS DesignModeler®, ANSYS Inc., Canonsburg, Pennsylvania, USA). For shoes with repeated pattern geometries, CAD models were developed. For shoes with irregular tread patterns, laser scans were collected, processed to repair surface irregularities (Geomagics®, 3D Systems Corporation, Rock Hill, South Carolina, USA), and tread surface texturing was added to the surface based on the texture's shape, size and orientation (ANSYS DesignModeler®). Since viscoelastic effects were accounted for in the microscopic models, a linear elastic material based on durometer readings was used for the shoes in macroscopic models (Section 2.2).

Displacements and rotations of nodes at the bottom surface of the flooring and top surface of the shoe in the macroscopic models