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Parametric investigation of soft-body penetration into parallel-ridged textured surfaces for tactile applications

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ABSTRACT

The tribological interactions between skin and textured surfaces has profound impact on both the tactile perception of the product being used, as well as the functionality of the product with regards to friction coefficient. Previous work has shown that parallel-ridged textures have vastly different friction coefficients with regards to the direction of skin sliding, and that penetration of the skin into the voids between ridges not only add contact area but also potential for interlocking. The ability to model skin penetration into textural elements would prove to be very useful for predicting friction; however, the mechanics of the problem are incredibly complex such that they rule out a closed-form analytical solution. The authors investigated soft-body penetration using a non-dimensional computational approach based on the elastic properties of skin, as well as the texture ridge geometry parameters, as well as the normal loading. Model results were verified experimentally. The model was applied to a number of different combinations of ridge parameters and it was found that the amount of penetration could be predicted very well using a simple exponential relationship among the nondimensional terms. Texture groove width and applied normal load played a dominant role in penetration. These results yield a quantitative mechanics model which can be integrated into an overarching frictional model to predict skin on texture behavior due to both adhesion and edge interlocking.

1. Introduction

Tactile friction and perception are of great interest to engineers and product designers because of the number of products which are handled every day that require suitable surface characteristics to serve their function or to please the user. Perception enables us to judge characteristics of materials that we interact with whether they are cosmetic or functional. On the cosmetic side, tactile perception has been shown to influence our perception and feeling toward products (Chen et al., 2009; Childs and Henson, 2007; Barnes et al., 2004). On the other hand, the frictional components of tactile perception can allow us to distinguish between materials (Bergmann Tiest, 2010) and indicate to us if we need to apply more or less force when handling an object whether to influence grip or reduce abrasion. Thus, engineered surfaces are often optimized for their frictional purposes. For example, low friction surfaces such as the mouse pad of a laptop allow for ease of movement while high friction surfaces such as tool handles, phone cases, railing, and gym weights are all designed to give the user grip.

It has been shown that tactile friction can be reasonably modeled as a summation of friction from adhesion and deformation (Adams et al., 2007), adhesion being the dominant mechanism (Adams et al., 2007; Tomlinson et al., 2009). Experiments have shown that coefficient of friction decreases as surface roughness is increased from a nominally smooth surface (Skedung et al., 2010; Derler et al., 2009). This has been attributed to a reduction in real contact area reducing the amount of adhesion between the two surfaces. However, once a certain roughness is achieved the friction increases sharply. Tomlinson et al. (Tomlinson et al., 2011) experimented with triangular ridged surfaces of varying sizes and showed that when the surface roughness was increased to a certain threshold, an increase in friction was seen. This is attributed to an increase of the deformation component of friction by viscoelastic hysteresis and interlocking. They also noted that when groove depth was shallow, adhesion still occurred because the penetration of the finger into the grooves had reached the bottom of the groove channels. Darden et al. (Darden and Schwartz, 2013) hypothesized about the same phenomenon when testing the effect of sliding direction on friction against parallel-ridge textures. They investigated the sliding of a spherical neoprene probe parallel to and perpendicular to the orientation of ridges on a simple

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parallel-ridge textured surface. When the textural ridges were below a certain height, the coefficient of friction did not exhibit a change with sliding orientation, whereas ridges above this height showed a marked sliding orientation effect. Taylor and Lederman showed that the penetration of the finger into the groove is also an important factor in perception of roughness and developed a model to predict perceived surface roughness of parallel ridged surfaces as a function of penetration, groove width, and finger force (Taylor and Lederman, 1975). Zhang et al. further investigated such ridged surfaces and confirmed that the direction of sliding has a profound effect on the mechanisms of friction, which suggests that penetration of the soft fingertip into the intra-groove voids may contribute both to additional contact area as well as collision with ridge edges (Zhang, 2015). Correlations have been found between perceived roughness and friction (Chen et al., 2009; Bergmann Tiest, 2010; Smith et al., 2002). Numerous studies have also shown an increase in perceived roughness as groove width increases (Smith et al., 2002; Lederman, 1981; Kawasoe et al., 2008) which plays a crucial role in the amount of penetration that occurs.

The mechanics at the finger-on-texture interface are very complex, however, finite element analysis (FEA) has been utilized to model the interaction between fingers and surfaces to account for the complexities of the interaction and to analyze the stresses produced within the finger. Xydas et al. (2016) utilized FEA to determine the effect of adhesive friction on contact area of a finger on a flat surface using experimental friction measurements. Maeno et al. (Maeno et al., 1998) utilized FEA to model the internal stresses within the finger during movement along a flat surface taking into account the epidermal ridges, papillae, and bone and found that tactile receptors are appropriately located in areas of maximum von Mises stress produced by the shearing of the epidermal ridges. Shao et al. (Shao et al., 2010) conducted a similar FEA study analyzing the effect of epidermal ridges on the oscillation of friction force and location of maximum von Mises stress when the finger interacts with a textured surface.

Because of the observed impact on friction coefficient of fingertip penetration into textural features, this investigation sought to better understand the mechanics of penetration of the finger into textural grooves, because of its importance in designing textures with desired levels of friction or perceived roughness. Accurately predicting the amount of penetration into textural grooves would help to predict the likelihood of micro-adhesion at the bottom of the groove channels, provide insight in the perception of surface roughness, and possibly provide insight to predicting the amount of friction due to deformation. There currently lacks an analytical solution, such as those presented by Hertz for the contact distance of a cylinder against a rigid plane, for the penetration of a cylinder as it is compressed against a rigid grooved surface.

The objective of this study was to develop a model to predict the amount of penetration of a soft cylindrical body into a rigid parallel rectangular grooved surface to simulate finger-on-texture contact. The parameters considered in this interaction included the widths of the surface grooves and ridges as well as the radius of the cylinder, elastic modulus, and applied pressure. Parameters of similitude were non-dimensionalized with one another as input variables to make the model applicable to both the micro and macro scale. An analytical mechanical approach was taken as a basis of the relationship between applied load and penetration. The model was developed by the regression of the penetration results of numerous FE simulations which varied the groove width in a particular range of interest applicable to the surface textures used in experiments of Darden et al. (Darden and Schwartz, 2013). The effect of multiple grooves on penetration was also analyzed in order to better model realistic textures.

2. Methods

The methodology of this investigation was to develop a model to predict penetration of an elastomeric cylindrical body into rectangular rigid grooves, based on textural geometry parameters and elastomer stiffness. To attain this goal, an FE model of both the cylinder and texture were developed and studied. FE results were compared to data collected from an experimental apparatus in order to validate the FE model, and finally the effects of additional grooves were studied using the model. The dimensionless parameters of the model were determined by dimensional analysis via Buckingham Pi theory. This approach allows for the development of a scale-invariant conceptual model of a system using dimensionless terms in order to evaluate results when experiments are run at different size and/or time scales compared to the original phenomenon. The approach is commonly used in experimental fluid mechanics and heat transfer, but also provided value in this work. The structure of the proposed non-dimensional model was determined both by an analytical technique and using a least squares regression to several data resulting from numerous FEA simulations.

2.1. Texture parameters and similitude approach

The modeled textures were two-dimensional parallel ridges with rectangular cross section. The space between the ridges (referred to as ‘grooves’) is referred to as ‘*b*’, while ridge is referred to as ‘*a*’. The cylinder which was loaded into the textured is defined by its radius, *R*, elastic modulus, E, and Poisson ratio, *ν*. A load was applied to a rigid horizontal plate which rested above the cylinder. The applied load per unit length, divided by the cylinders diameter is denoted by ‘*p*’. The output parameter of interest is the total penetration, δ_{tot}, of the cylinder into the central groove. The total penetration is a combination the initial penetration, δ_{i}, as the cylinder rests atop the central groove without any external loading, and the forced penetration, δ_{f}, which is the penetration caused from the applied loading. The initial penetration (based solely on cylinder radius and groove width) was calculated using trigonometry of a circle of radius, *R*, resting atop two ridges with a fillet radius, *r*, spaced a distance, *b*. This initial penetration, δ_i, can be calculated by

$$\delta_i = R + r - \sqrt{(R+r)^2 - \left(\frac{b}{2} + r\right)^2} \tag{1}$$

While the fillet radius affects δ_{i}, for the purpose of this experiment, it is assumed to be small enough to have a negligible effect on δ_{f}. Fig. 1 shows both the uncompressed and compressed state of a cylinder interacting with a grooved surface. Dimensionless parameters of similitude were selected as input parameters for the model through the use of Buckingham Pi theory. From these parameters, there were two dimensions including length and force. This left the unique variables in each Π term to be δ_{f}, *p*, and *b*, respectively.

The use of dimensional analysis yielded the output dimensionless parameter involving penetration, δ_f/R, and the input parameters p/E and b/R which depend on load, geometry and material properties. The contribution from each input parameter was determined by the analytical and FEA methods in the following sections.

2.2. Mechanics basis for finite element approach

In an attempt to determine an analogous phenomenon that possessed a closed-form analytical solution to serve as the basis of a regression model, the penetration of the cylinder into the