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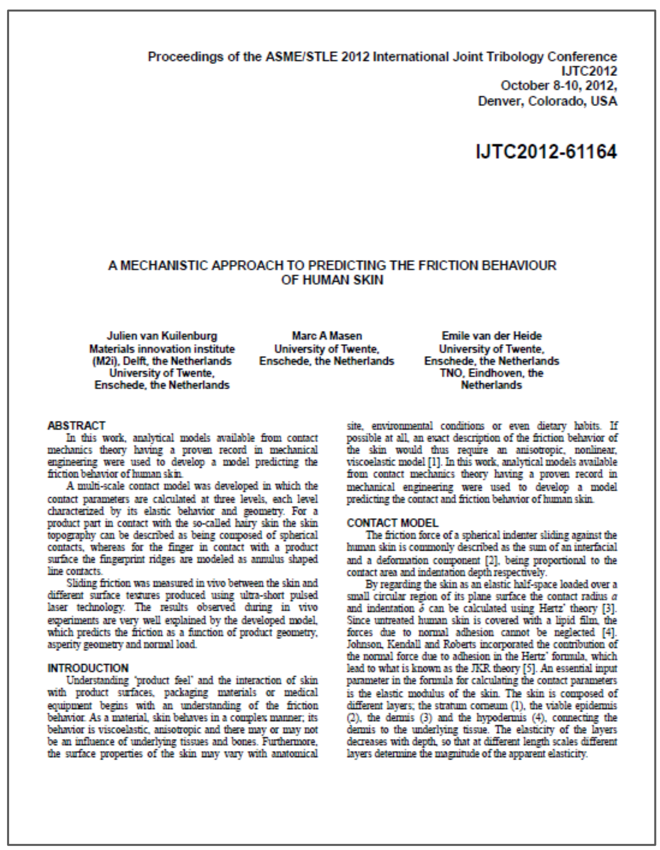

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A MECHANISTIC APPROACH TO PREDICTING THE FRICTION BEHAVIOUR OF HUMAN SKIN

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ABSTRACT

In this work, analytical models available from contact mechanics theory having a proven record in mechanical engineering were used to develop a model predicting the friction behavior of human skin.

A multi-scale contact model was developed in which the contact parameters are calculated at three levels, each level characterized by its elastic behavior and geometry. For a product part in contact with the so-called hairy skin the skin topography can be described as being composed of spherical contacts, whereas for the finger in contact with a product surface the fingerprint ridges are modeled as annulus shaped line contacts.

Sliding friction was measured in vivo between the skin and different surface textures produced using ultra-short pulsed laser technology. The results observed during in vivo experiments are very well explained by the developed model, which predicts the friction as a function of product geometry, asperity geometry and normal load.

INTRODUCTION

Understanding 'product feel' and the interaction of skin with product surfaces, packaging materials or medical equipment begins with an understanding of the friction behavior. As a material, skin behaves in a complex manner; its behavior is viscoelastic, anisotropic and there may or may not be an influence of underlying tissues and bones. Furthermore, the surface properties of the skin may vary with anatomical site, environmental conditions or even dietary habits. If possible at all, an exact description of the friction behavior of the skin would thus require an anisotropic, nonlinear, viscoelastic model [1]. In this work, analytical models available from contact mechanics theory having a proven record in mechanical engineering were used to develop a model predicting the contact and friction behavior of human skin.

CONTACT MODEL

The friction force of a spherical indenter sliding against the human skin is commonly described as the sum of an interfacial and a deformation component [2], being proportional to the contact area and indentation depth respectively.

By regarding the skin as an elastic half-space loaded over a small circular region of its plane surface the contact radius a and indentation δ can be calculated using Hertz' theory [3]. Since untreated human skin is covered with a lipid film, the forces due to normal adhesion cannot be neglected [4]. Johnson, Kendall and Roberts incorporated the contribution of the normal force due to adhesion in the Hertz' formula, which lead to what is known as the JKR theory [5]. An essential input parameter in the formula for calculating the contact parameters is the elastic modulus of the skin. The skin is composed of different layers; the stratum corneum (1), the viable epidermis (2), the dermis (3) and the hypodermis (4), connecting the dermis to the underlying tissue. The elasticity of the layers decreases with depth, so that at different length scales different layers determine the magnitude of the apparent elasticity.

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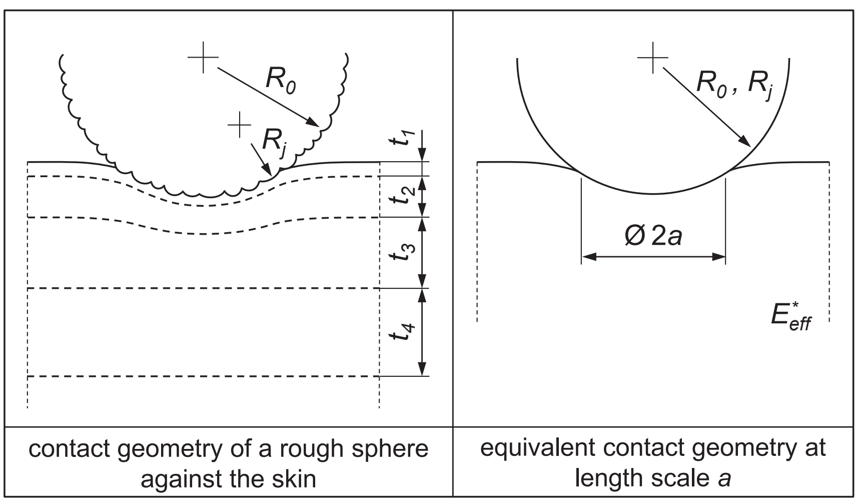

Figure 1. Schematic illustration of the concept of the effective elastic modulus

Elastic properties

To account for the multilayered and nonhomogeneous structure of the skin, the concept of an effective elastic modulus was adopted, which led to a closed form expression $E = f(a)$ describing the elasticity of the skin as a function of length scale [6]. This is depicted schematically in Fig. 1. In case of a spherical contact the length scale of the contact equals the contact radius a. Figure 2 shows that the effective elastic modulus of the volar forearm varies considerably with length scale. At different scales the evolution of the effective elastic modulus with contact length scale can be described using a power law, which enables substitution into the available contact mechanics formula.

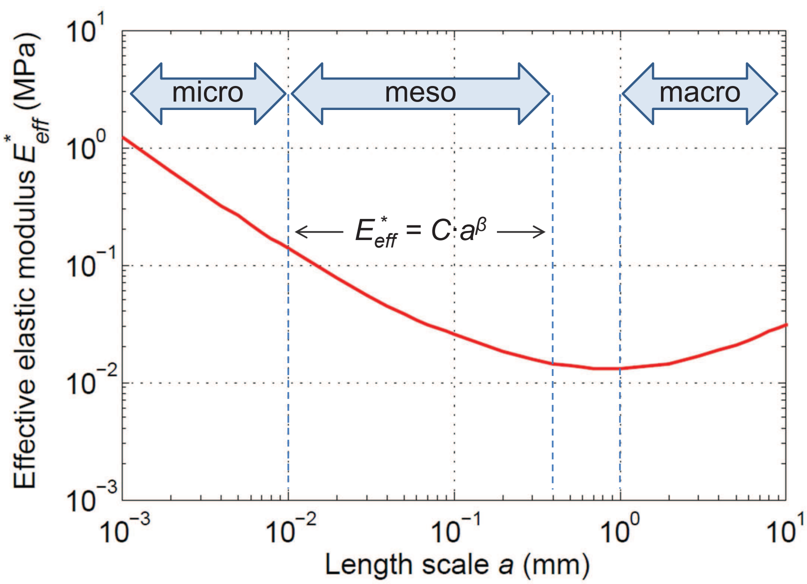

Figure 2. Effective elastic modulus of the skin of the volar forearm as a function of length scale. Adapted from [6]

Surface topography

To incorporate the influence of the skin microrelief a multi-scale contact model was developed in which the surface topography of the skin is considered as a nominal flat surface having a bi-sinusoidal profile characterized by a wavelength and amplitude [7]. An average radius of curvature R_i was calculated after measuring surface feature density and roughness amplitude R_z. For a smooth spherical probe in contact with the skin of the volar forearm this simplified geometry is illustrated in Fig. 3. The contact areas of the individual surface features are calculated using the theory proposed by Archard [8]; as a result of the Hertzian pressure distribution the area of the contact spots in the center of the macro contact is considerably larger than the area of the contact spots at the edge.

Friction

The friction force is calculated from the real contact area and the indentation at the macro scale. The evolution of the friction force F with normal load F was calculated for nine

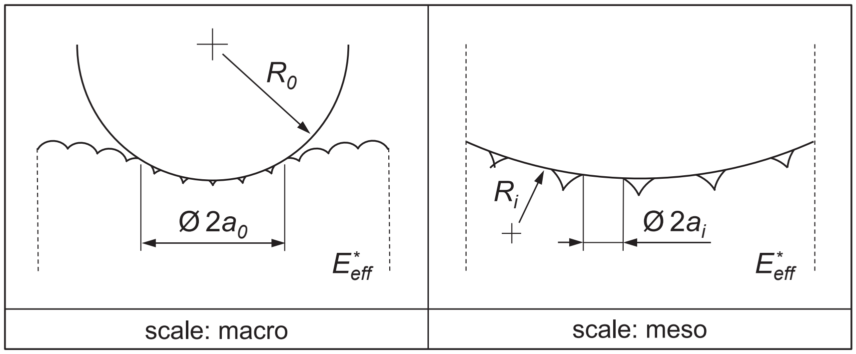

Figure 3. Contact dimensions of a smooth spherical probe in contact with the skin of the volar forearm.

different cases reported in literature using the two-term friction model [2]:

$$F_\mu = F_{\mu,adh} + F_{\mu,def} \approx kF^n \quad (1)$$

From analysis of the different studies it was found that the power n varies with experimental conditions [9]. For cleaned skin n is larger than 1. For untreated skin n is smaller than 1 due to the increasing contribution of normal adhesion, and for wet skin eventually. Comparison of calculated and reported values for n shows good agreement as shown in Fig. 4.

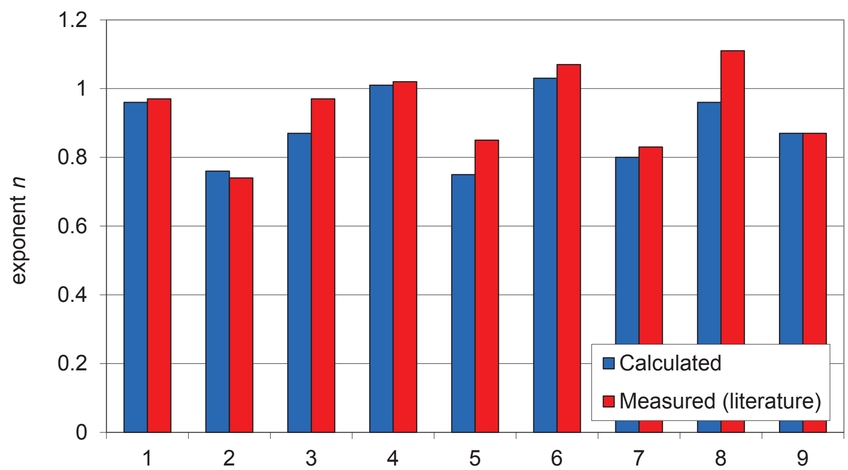

Figure 4. Comparison of model predictions with experimental results collected from literature. Adapted from [9].

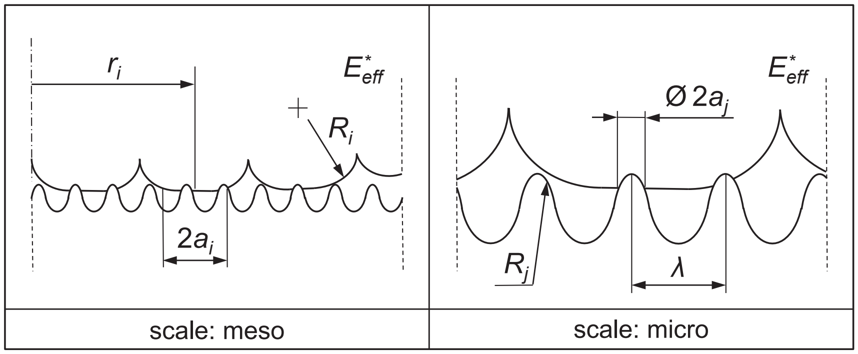

Figure 5. Contact dimenstions of the fingertip ridges in contact with a regular surface texture.

TEXTURED SURFACES

To investigate the friction behavior at the asperity-level, surface textures consisting of evenly distributed spherically-tipped asperities were produced using ultra-short pulsed laser technology (www.lightmotif.nl). The texture parameters tip radius R and spacing λ varied between 2 and 10 µm and 20 and 100 µm respectively. Sliding friction was measured in vivo between the skin of the fingerpad and textured metal samples measuring 20×40 mm^2 using a 6 DOF load cell (ATI Gamma, www.ati-ia.com). The surface topography of the fingerpad was measured from a silicone replica using a 3D optical profilometer (VK-9700, www.keyence.com). Hydration level of the skin and thickness of the lipid layer were monitored during the experiments using a Corneometer CM825 and Sebumeter SM815 (www.courage-khazaka.de). The contact of the fingerpad with a nominally flat, rigid surface can be described analogous to the smooth spherical probe in contact with the flat skin by considering the fingerpad as a deformable sphere. The fingerprint ridges are modeled as annulus shaped line contacts, characterized by a radius r_i and contact width $2a_i$. When in contact with a surface texture which is composed of spherically-tipped asperities, the real area of contact is determined by the contact behavior at the micro scale as depicted schematically in Fig. 5. In this case the friction force is calculated from the real area of contact and the indentation of the asperities at the micro scale. Figure 6 shows the results obtained from experiments (dots). The calculated coefficient of friction is plotted as a function of tip radius R and spacing between asperities λ (lines). The coefficient of friction increases with increasing tip radius. This effect can be attributed to the increasing contribution of normal adhesion, which is confirmed by JKR theory. At constant tip radius the coefficient of friction shows a strong decrease with increasing spacing. At larger spacing the coefficient of friction tends to increase with increasing spacing. The two-term friction model shows that at small spacing the friction force arises mainly from interfacial shear, which decreases with increasing spacing, whereas at large spacing the deformation component cannot be neglected anymore.

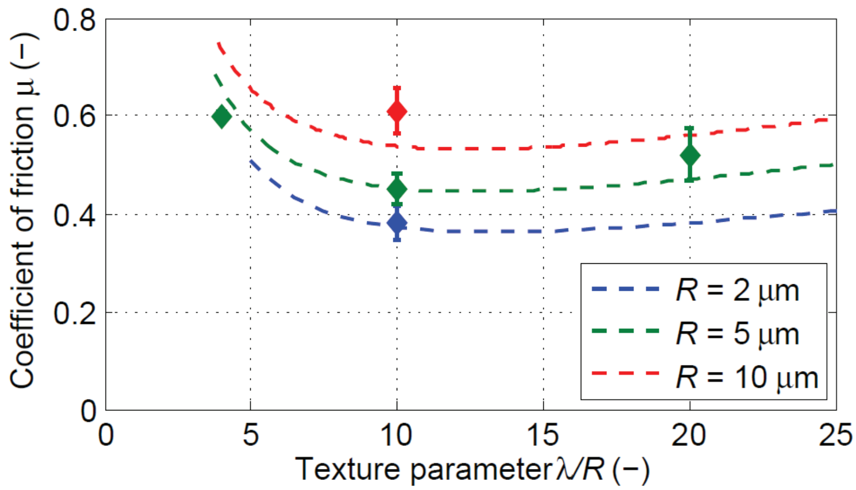

Figure 6. Coefficient of friction of the fingerpad sliding against a surface texture as a function of tip radius R and spacing λ: experimental results (dots) and modeling results (lines).

CONCLUSIONS

The results observed during in vivo experiments are very well explained by the developed contact and friction model, which predicts the friction as a function of product geometry, asperity geometry and normal load. Further work will involve the definition of design rules for the engineering of surfaces in contact with the skin, which are based on the friction model.

ACKNOWLEDGEMENTS

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