Random switch of adhesion and deformation friction depending on material hardness

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***Abstract*—The friction between a rigid body and skin was assumed to be a summation of adhesion and deformation friction in prior literature. In this study, the friction, when a finger slides over the artificial skin model is measured and it is determined that adhesion and deformation friction occur probabilistically. Furthermore, the probabilities of occurrence change depending on the material hardness. These findings are different from the previous reports which suggest that both adhesion and deformation friction simultaneously contribute to the total friction with constant ratios that do not change probabilistically. Understanding such tribological properties can lead to the development of artificial skins with a comfortable sense of touch.**

***Index Terms*—Skin friction, adhesion, deformation, artificial skin**

I. Introduction

Understanding the frictional characteristics of skin is useful for designing skin care products and artificial skins. Previous studies investigated the contribution of adhesion and deformation friction to the total friction between a rigid body and skin. Mahdi et al. found that the total frictional force was a linear combination of the adhesion and deformation friction components, and adhesion friction was dominant under dry conditions [1]. Derler et al. measured the friction between glass plates and human skin and found that adhesion friction was more dominant compared to the deformation friction [2]. These studies demonstrated that adhesion and deformation friction acted simultaneously, and in general, adhesion friction was dominant in the dry conditions [1]–[3].

However, the accuracy of the above findings for friction between skin-skin contact remains to be determined. In this study, it is demonstrated that either type of friction can be dominant in the interaction between a finger and artificial skin, and the dominance switches probabilistically. The dominance of either adhesion or deformation friction was investigated during a single finger sliding motion on the artificial skins based on the normal force dependence of the coefficient of friction. Furthermore, the changes in the probabilities of occurrence according to the material hardness are examined.

II. Friction model

Skin friction is attributed to two main mechanisms, namely, adhesion and deformation. The coefficient of friction is the sum of these two components, and is expressed as follows [4]:

$$\mu = \mu_{ad} + \mu_{def}, \tag{1}$$

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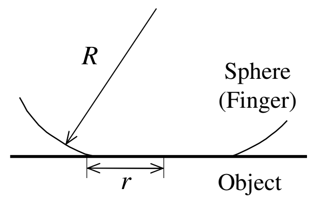

Fig. 1. Contact plane between a finger and a flat surface as described by Hertzian contact theory

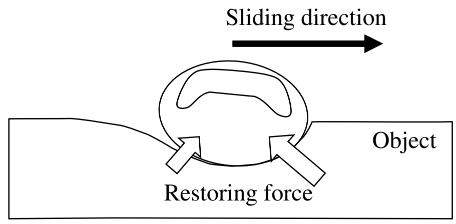

Fig. 2. Schematic diagram of deformation friction

where μ, μ_{ad}, and μ_{def} are the coefficient of friction between two materials, coefficient of adhesion friction, and coefficient of deformation friction, respectively.

Adhesion friction is based on the concept that the adhesion of the real contact area between two elastic bodies is broken with the interfacial shear strength τ. Fig. 1 shows the scene of a finger pad touching an elastic plane. According to Hertizan contact theory, when a sphere imitating a finger pad with a radius of R pushes an elastic plane with a load f_n, the contact area of the two elastic bodies is a circle with a radius of r. Here, the contact area A of the two elastic bodies is proportional to the $2/3$ power of the contact force in the normal direction:

$$\begin{aligned} A &= \pi r^2 \\ &\propto f_n^{\frac{2}{3}}. \end{aligned} \tag{2}$$

Then, the coefficient of adhesion friction is proportional to the negative power function of the normal force [4]:

$$\begin{aligned} \mu_{ad} &= \frac{\tau A}{f_n} \\ &\propto f_n^{-\frac{1}{3}}. \end{aligned} \tag{3}$$

In contrast, deformation friction originates from the restoring force of the deformed material. Fig. 2 is the schematic of deformation friction. Deformation friction force, F_{def}, is proportional to the $4/3$ power of the normal force [5]:

$$F_{def} \quad \propto \quad {f_n}^{\frac{4}{3}}. \tag{4}$$

Then, the coefficient of deformation friction, μ_{def}, is proportional to the positive power of the normal force:

$$\begin{aligned} \mu_{def} \quad &\propto \quad \frac{{f_n}^{\frac{4}{3}}}{f_n} \\ &\propto \quad {f_n}^{\frac{1}{3}}. \end{aligned} \tag{5}$$

Hence, the coefficient of friction, μ, is generally expressed as the power function of the normal force:

$$\mu = \alpha {f_n}^{\beta}. \tag{6}$$

β is negative when adhesion friction is dominant, and β is positive when deformation friction is dominant, according to (3) and (5), respectively.

III. Experiments

A. Method and Apparatus

The data analyzed in this study were acquired in our previous research [6]. The normal and shear forces generated between the finger and artificial skins were measured using two axial force sensing units assembled by our research group [7], [8]. The coefficient of friction was calculated as the ratio of the shear force to the normal force. The sampling frequency was 2 kHz for the force measurements.

Commercially available artificial skins (Bioskin, Beaulax Ltd., Japan) with two levels of hardness were used in the experiment. Their thicknesses were 5 mm and their surfaces were covered with a thermoplastic polyurethane thin film for all skins, i.e., the surface materials were the same. Shore AO hardness of artificial skins and fingertips were measured using a durometer (GS-721N, Teclock, Japan) in accordance with ISO 7619-1. Those of the hard and soft artificial skins were 19.1 and 3.2, respectively, and those of the fingertips of the participants were 9.0 ± 2.1.

Each of the eleven male participants in their 20s rubbed the surface of the artificial skin set on the measurement instrument for 10 s in a single trial. Each model was tested thrice. Before each trial, the fingertips of the participants and material surfaces were wiped with a dry cloth to remove the moisture or sweat.

B. Data Analysis

The relationship between μ and f_n was approximated in the form of (6) for each finger slide. Fig. 3 shows examples of fitting results. The exponent β is classified into three patterns, namely, significantly positive, significantly negative, and not significantly different from zero at $p < 0.05$. Here, 192 and 182 slides were analyzed for hard and soft materials, respectively.

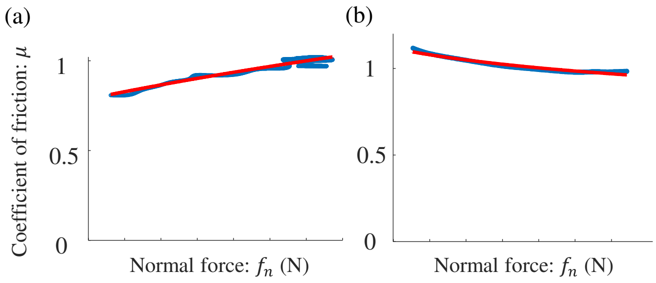

Fig. 3. Data plots and fitting results of the relationship between μ and f_n. Red curves represent the fitting curves and blue dots correspond to the observed coefficients of friction. (a) β is positive, and deformation friction is dominant. (b) β is negative, and adhesion friction is dominant.

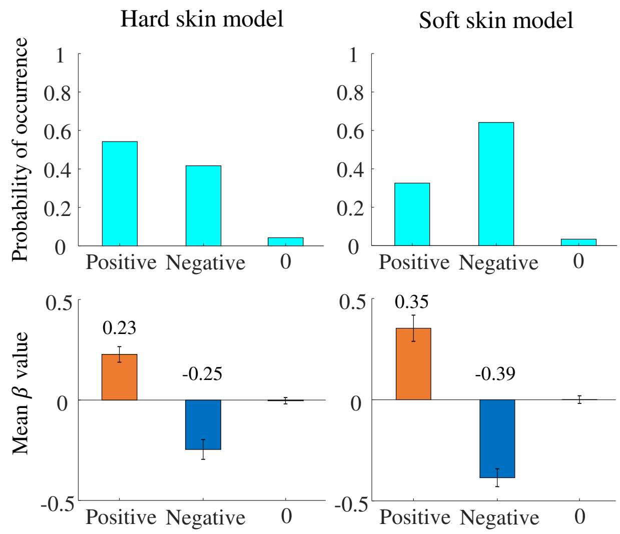

Fig. 4. (Top) Probabilities of occurrence of the slides with positive, negative, and insignificant β values. (Bottom) Mean values of β for each condition. The orange and blue bars represent the significantly positive and negative values, respectively.

IV. Results

The occurrence rates for the slides with positive and negative β values and insignificant β values are shown in the upper part of Fig. 4. The mean values of β for each class are shown in the lower part.

For the soft skin model, the mean β value was approximately $1/3$, when β was significantly positive. Furthermore, it was approximately $-1/3$, when β was significantly negative. For the hard skin model, the mean β value was 0.23 for the slides with positive β, and -0.24 for the slides with negative β. The absolute values of β were lower for the hard skin model than those for the soft skin model. The normal force dependency of the coefficient of friction was lower for the hard skin than that for the soft skin.

If the skin friction is expressed as a linear sum of adhesion and deformation friction as reported in previous studies [1], [2], β should be constant for all finger slides. However, in the case of hard skin models, the possibilities of the occurrence of positive and negative β values were almost similar, or that of positive β value was slightly higher. Adhesion and deformation friction occurred at similar probabilities when rubbing the hard surfaces. Additionally, for soft skin models, the probability of negative β values was high, and adhesion friction was more dominant. These results indicate that the dominance of the two frictional modes changes stochastically, which is contrary to the previous understanding that the total friction is expressed as a linear combination of adhesion and deformation friction.

V. CONCLUSIONS

The probabilities of dominance of adhesion and deformation friction during the rubbing of artificial skins were investigated. The friction encountered during the finger slides was classified into three cases, namely, adhesion friction, deformation friction, and friction that follows Amontons' law, where the coefficient of friction does not depend on the contact force. Contrary to the previous findings, either adhesion or deformation friction was saliently observed for each slide. Furthermore, the probabilities of occurrence of these two types of friction modes changed with the variation in the hardness of artificial skin. For skin model that was softer than a finger, adhesion friction was more likely to occur. These findings may contribute to the product design in reducing friction by considering the difference in the normal force dependence of the coefficient of friction depending on the material hardness.

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