Effect of Material Hardness on Friction Between a Bare Finger and Dry and Lubricated Artificial Skin

Koki Inoue, Shogo Okamoto, Yasuhiro Akiyama and Yoji Yamada

***Abstract*—Understanding the tribological phenomena when fingers slide over soft surfaces such as skin is important for many practical applications. Therefore, this study analyzed the coefficients of friction for a bare finger sliding over artificial skin with different hardness under dry and lubricated surface conditions. This study contrasts with previous research that predominantly analyzed the contact between skin and hard surfaces or probes. Under dry conditions, the coefficient of friction was constant for artificial skins that were harder than the finger pad, irrespective of the normal force of the finger. However, the coefficient of friction decreased with increasing normal force for softer artificial skins. When the surface of the artificial skin model was lubricated with mica, the coefficient of friction exhibited normal-force dependence only for soft artificial skins, similar to the observations under dry conditions. This effect was due to the deformation friction; thus, the coefficient of friction increased as the normal force increased. Conversely, when the model was lubricated with TiO_2, the coefficient of friction depended on the normal force for all hardness levels. These findings provide insights into the friction experienced during skin-skin or skin-soft material contact under dry and lubricated conditions that can easily occur in daily life. Thus, the results of this study can be useful for the development of skin care products or assistive robots involving human-robot contact.**

I. Introduction

HUMANS regularly touch their skin using their fingers. Therefore, it is important to understand the tribological phenomena that occur when fingers slide over soft surfaces such as skin for the development of products such as cosmetics. Specifically, this study focuses on the relationships between the coefficient of friction (cof), the normal force, and the sliding speed when an artificial skin surface is rubbed by a human finger.

Previous studies have investigated these relationships between skin and rigid probes. They found that the cof generally decreases with increasing normal force at the point of contact between the human skin and the rigid probe by a power of approximately $-1/3$ of the normal force (e.g. [1], [2], [3], [4], [5], [6]). However, the normal-force dependence of the cof differs depending on the probes and other conditions used in the experiment. For example, Wei et al. slid a polypropylene ball along the forearm and reported that cof increases with increasing normal force of 0.1–0.9 N [7]. Conversely, Naylor et al. reported a constant cof between the skin surface and a polyethylene probe of approximately 0.5 for a normal force range of 2–7 N [8]. Furthermore, Egawa et al. measured a constant cof on the forearm when the normal force ranged from 0.244–0.589 N [9]. These results [8], [9] support Amontons' law that the cof does not depend on the normal force.

Some studies have analyzed the cof under different surface lubrication conditions. For example, Adams et al. measured the friction between the forearm and glass or polypropylene hemisphere probes under dry and wet conditions. For both probes, the cof did not vary with normal force under dry conditions, whereas the cof decreased with increasing normal force under wet conditions [10]. In the work of Dzidek et al., under dry conditions, the cof between a finger and a glass decreased as the normal force increased, whereas the cof between a finger and a smooth polypropylene surface increased with increasing normal force. Furthermore, when the surface was wet with sweat, the cof decreased with increasing normal force for both materials. In contrast, the cof between a finger and a rough polypropylene surface was constant regardless of the normal force under both dry and wet conditions [11]. Derler et al. measured the friction between rough or smooth glass plates and human skin under dry and wet conditions. They found that the cof did not depend on the normal force in one case and decreased with the increasing normal force in another case [12]. The effects of moisturization on the skin tribological system have also been studied in [11], [13]. As mentioned above, for skin-object contact, the effects of normal force on the cof depend on the material and other conditions such as wetness and roughness. Most of these studies employed a rigid probe to rub human or artificial skin or utilized a finger on rigid surfaces. However, only a few studies have examined the normal-force dependence of the cof when a bare finger slides on a soft material such as skin.

Therefore, this study conducts experiments to measure the friction caused by a finger sliding over the surface of artificial skin models that imitate the surface asperity and seven hardness levels of human skin. These experiments replicate the conditions of a finger touching skin. We then investigate how the cof depends on the material hardness, the normal force, and the sliding speed. Three surface conditions are analyzed: dry skin and skin lubricated with mica and titanium dioxide powders. The observed phenomena are explained according to the normal-force dependence of the contact area, which is unique to pressing with a finger and does not occur when pressing with a rigid probe. The contact area is expressed as a power function of the normal force, where the exponent changes with normal force during finger pushing.

II. Model for the normal-force dependence of the coefficient of friction

A. Hertzian contact theory

When considering the contact area during finger touching, the Hertzian contact theory is used, which describes the relationship between the deformation, contact surface, and reaction force for two elastic bodies in contact. This theory is based on various assumptions such as the occurrence of a small strain when two elastic bodies come into contact. Therefore, this theory is not strictly applicable to human fingers but is often used to obtain a general understanding of the tribological phenomenon.

Fig. 1 shows the state of a sphere imitating a finger pad touching the elastic plane. When a sphere with a radius of R_f (imitating a finger pad) pushes an elastic plane with a load f_n, the contact surface of the two elastic bodies is a circle with a radius of r. Here, the apparent contact area A of the two elastic bodies is expressed as:

$$\begin{aligned} A &= \pi r^2 \\ &= \pi \left(\frac{3R}{4E^*}\right)^{\frac{2}{3}} {f_n}^{\frac{2}{3}}, \end{aligned} \tag{1}$$

where E^* is the effective elastic modulus given by the elastic moduli and the Poisson's ratios of the two elastic bodies. R is the effective

Department of Mechanical Systems Engineering, Nagoya University, Furo-cho, Chikusaku, Nagoya 464-8603, Japan.

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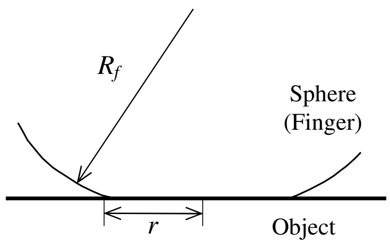

Fig. 1: Contact plane between a finger and a flat surface as described by Hertzian contact theory

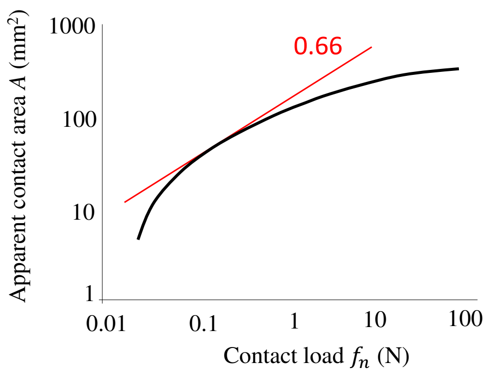

Fig. 2: Relationship between contact load and apparent contact area of the finger pad, adapted from Kuilenburg [17]

radius, which is determined by the radius of the two elastic spheres. The effective radius R is equal to R_f if the elastic body pushed by the finger is a plane.

B. Coefficient-of-friction model based on Hertzian contact theory

Adhesion friction is the dominant type of friction between the skin and a flat surface [6], [14], [15]. This type of friction is based on the concept that the adhesion of the real contact area A_r is broken with interfacial shear strength τ. When the apparent contact area and the real contact area are the same, the cof is simply modeled to be proportional to the $-1/3$ power of the normal force f_n as follows:

$$\begin{aligned} \mu &= \frac{\tau A_r}{f_n} \\ &= \tau\pi\left(\frac{3R}{4E^*}\right)^{\frac{2}{3}} {f_n}^{\frac{2}{3}-1} \qquad (2) \\ &\propto {f_n}^{-\frac{1}{3}}. \qquad (3) \end{aligned}$$

Thus, in this coefficient-of-friction model, the cof is described as the power function of the normal force:

$$\mu = \alpha {f_n}^{\beta}, \qquad (4)$$

where α and β; i.e., the exponent of the normal force, are constant values. Note that in the finger contact, the real contact area is not the same as the apparent contact area because of the finger ridges and surface roughness [16].

C. Normal-force dependence of the contact area

Fig. 2 shows the simplified double-logarithmic graph summarized by Kuilenburg [17], which describes the experimental relationship between the normal force and the apparent contact area when a finger is pressed against a rigid surface. According to Hertzian contact theory, as in (1), the apparent contact area A is proportional to the $2/3$ power of the normal force f_n; i.e., the gradient of the graph in Fig. 2 is approximately 0.66. However, when the normal force is small, the gradient is greater than 0.66, and when the normal force is larger than approximately 1 N, the gradient is less than 0.66. Therefore, during frictional rubbing with a finger, the exponent β is not constant but can change with the normal force. Such nonlinearity is a phenomenon peculiar to pushing with a finger and has not been discussed in friction studies using a rigid probe.

D. Coefficient-of-friction model considering the normal-force dependence of the fingertip

For the case where a finger slides on a surface, we propose a novel cof model as follows:

$$\mu = a{f_n}^{bf_n+c} + dv, \qquad (5)$$

where the power function of the normal force in the equation represents the change of gradient between the apparent contact area and the normal force, as in Fig. 2. Here, v indicates the sliding velocity. In (5), the exponent is a function of the normal force expressed using b and c. Using this exponent function, a phenomenon specific to pressing with a finger is expressed. Here, a represents the magnitude of the cof and depends on the material hardness, as described in (2). Furthermore, d is the component of speed dependence. In many cases, the cof monotonically increases or decreases with the sliding velocity [4], [5], [7], [14], [18], [19] or exhibits a peak at a moderate sliding velocity depending on the condition [18]. Under the condition used herein, the cof monotonically changed with the sliding velocity; thus, we expressed the effect of velocity as a linear function. As in the latter experiment, the effect of sliding velocity is significant and this component is necessary.

III. EXPERIMENTS

A. Two-axial force and sliding speed measurement

The cof generated between the finger and the artificial skin and the sliding speed during touching were measured using a two axial force sensing unit assembled by the authors' research group [20]. An overview of the device is shown in Fig. 3. The normal force was measured using two uniaxial force sensors (9313AA2, Kistler, Switzerland) installed in the lower part of the device, and the shear force was measured using a uniaxial high-sensitivity force sensor (9217A, Kistler, Switzerland) fixed to two metal pieces in the upper part of the device. The signals from both the normal and shear force sensors were amplified by two charge amplifiers (5073A2 and 5015, Kistler, Switzerland, nominal drifts: 0.005 N/s and 0.0003 N/s, respectively). We did not use low-pass filtering functions of the amplifiers. Fig. 5 shows examples of raw force data. Then, the cof was calculated as the ratio of the shear force to the normal force. Finger movement was measured using two wired encoders (MTL-12, MTL Co., Japan) by winding a wire attached to the encoders around a finger. The resolution of finger movement measurement is approximately 0.01 mm. The sampling frequency was set to 2 kHz for the two axial forces and the finger movement measurements.

B. Artificial skins used in the experiment

Artificial skins (Bioskin, Beaulax Ltd., Japan) with seven levels of hardness were employed, with the hardest level being 1 and the softest level being 7. All skins were 5 mm thick and their surfaces were covered with a thermoplastic polyurethane thin film, the surface asperity of which simulates that of human skin (roughness value, R_a: 7.6±1.9 μm [21]).

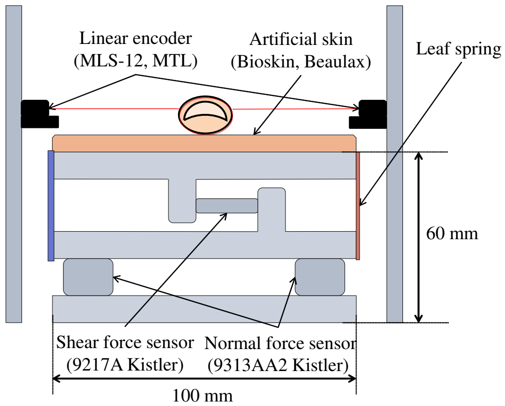

Fig. 3: Measurement setup

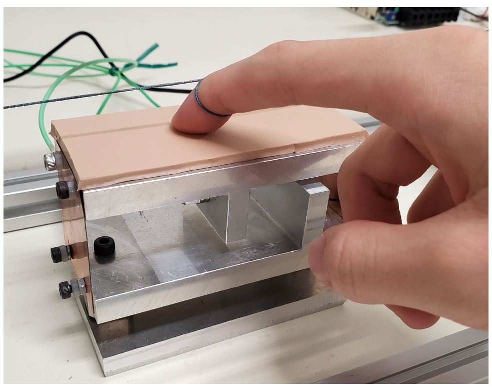

Fig. 4: Experimental setup

The shore AO hardness, which is a scale for soft rubbers, of the artificial skins was measured using a durometer (GS-721N, Teclock, Japan) in accordance with ISO 7619-1. An artificial skin was placed on a hard plane and the needle of the durometer was placed in static contact. A load of 200 gf was applied to the artificial skin, and the durometer reading was taken immediately after application of the load. This measurement was performed five times for each material and the median value was adopted. The hardness of each participants' finger was measured by the same process. Table I shows the result of the measurement. The value for the finger pad shows the average and standard error among all participants.

The experiment was conducted under three lubrication conditions: dry (no lubrication) and lubrication with two types of powder. Mica (mean particle size: 2 µm) and titanium dioxide (TiO_2, mean particle size: 0.25 µm) were used as the lubricants, which are commonly used in cosmetic products. Mica reduces friction and TiO_2 powder adheres to the skin.

C. Task

Participants rubbed the surface of the artificial skin attached to the measurement instrument for 10 s in a single trial. They were

TABLE I: Hardness of artificial skin models and human fingers. Shore AO hardness values conforming to ISO 7619-1. The unit is arbitrary. Higher values indicate harder materials.

Hardness lv.	1	2	3	4
Hardness	AO 19.1	AO 18.0	AO 16.9	AO 11.0
Hardness lv.	5	6	7	Finger
Hardness	AO 9.6	AO 7.8	AO 3.2	AO 9.0±2.1

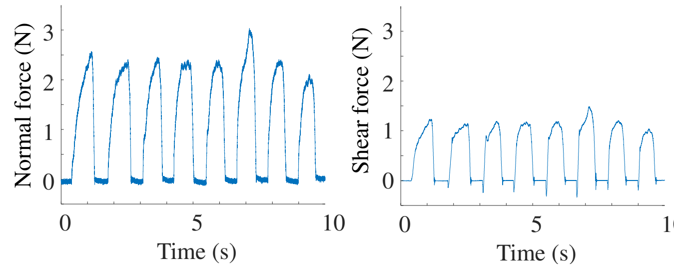

Fig. 5: Raw data of normal and shear forces

instructed to slide their index finger as if feeling the quality of the material. There were no instructions regarding the finger speed and force. Seven types of skin model were tested in a randomized order, and each hardness level was tested three and ten times for dry and lubricated conditions, respectively. There were fewer participants assigned to test the lubrication conditions than those for the dry conditions. In order to increase the reliability of the data, the lubrication experiment was performed 10 times. Before each trial, participants' fingers and the material surfaces were wiped with a dry cloth. The experimental setup is shown in Fig. 4.

D. Participants

Eleven males aged 20–29 participated in the experiment under dry conditions and eight males and one female aged 20–29 participated in the experiment under lubrication conditions. All participants provided informed consent and were unaware of the objectives of the study before the experiments.

E. Data processing

Before the main signal processing, we removed a linear drift component that was defined by the zero force levels before and after a trial. To analyze the kinetic friction, only data when the finger was clearly sliding on the skin model were used for the analysis. Specifically, only the observation points where both the normal force and shear force were at least 0.05 N and the sliding velocity v was at least 20 mm/s was used.

The relationship between μ, f_n, and v was approximated in the form of (5) for each trial using *Curve Fitting Toolbox* of MATLAB 2019a (e.g., Fig. 6). The success or failure of the fitting was judged on the basis of the determination coefficient R^2; trials in which R^2 was less than 0.35, which was determined arbitrarily, were excluded from the analysis due to low accuracy. For dry condition, in terms of the mean R^2 value, among the hardness levels, the highest was $R^2 = 0.52$ for hardness level 1 and the smallest was $R^2 = 0.46$ for hardness level 4. Among the participants, the mean R^2 ranged 0.42–0.56. For mica lubricated condition, among the hardness level, the highest was $R^2 = 0.63$ for hardness level 6 and the smallest was $R^2 = 0.50$ for hardness level 1. Among the participants, the mean R^2 ranged 0.42–0.70. For TiO_2 lubricated condition, among the hardness level, the highest was $R^2 = 0.55$ for hardness level 5 and the smallest was $R^2 = 0.47$ for hardness level 1. Among the participants, the mean R^2 ranged 0.40–0.56.

The variation of finger motions was substantial as follows. Even for the five trials with the smallest variations of normal force or speed, the mean and standard deviation of the range (difference between the maximum and minimum values) of the normal force was 1.31±0.41 N, which was observed for a trial for hardness level 4, and those of the sliding speed was 108±14.3 mm/s for hardness level 7 of the dry condition. These ranges are comparable to those during tactile exploration observed in a previous report [22].

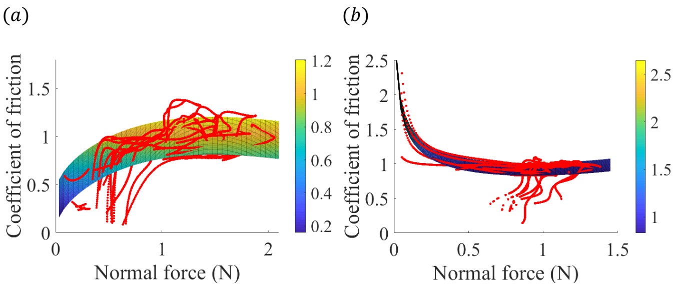

Fig. 6: Data plots and fitting results showing the relationship between coefficients of friction and normal force. Red dots are observed data. Colored curved planes are the fitting surface. (a) $R^2 = 0.60$. The power of f_n is positive. (b) $R^2 = 0.36$. The power of f_n is negative.

One-way ANOVA was conducted to determine the statistical differences among the seven levels of material hardness for a, b, c, and d. $p = 0.05$ was used to determine the statistical significance, above which every hardness pair was tested with no adjustment of p. Note that μ values were not statistically compared among the hardness levels because they do not depend on only the material hardness but also depend on f_n and v.

IV. Results

The means and standard errors of μ and a to d are shown in Fig. 7 for each lubrication condition and hardness level. Here, μ was simply computed as a ratio of the shear to normal forces. The statistics are summarized in the supplemental material.

A. Results under dry conditions

Softer materials generally exhibited greater a values, which is consistent with (2), where the cof is proportional to the negative power of the elastic modulus.

The b and c values must be analyzed in conjunction because they both determine the normal-force dependence of the cof. According to Fig. 7, both b and c were almost zero for hardness levels 1 to 3; i.e. for material that was harder than the finger. The cof did not depend on the normal force in these cases. For material that was comparable to or softer than the finger pad, b was negative and c was positive. As the normal force increased, the power function decreased, and the cof decreased.

d was significantly positive for all hardness levels; as the sliding speed increased, the cof increased. Also, d was relatively small for harder materials (levels 1–3) but relatively large for softer materials. These results suggest that the speed dependence of the cof is greater for softer materials, although this was only partly supported by the statistical results.

B. Results under mica-lubricated conditions

a increased with decreasing material hardness, except for hardness level 1. Under mica-lubricated conditions, the cof is proportional to the negative power of the elastic modulus. Also, mica exhibits lubrication properties because the a and cof values are smaller than those under dry conditions.

b was negative only for the softest material (level 7) and almost zero for all other hardness levels. The values of c were close to zero for harder materials (levels 1 and 2) and positive for softer materials (levels 5–7). In the case of harder materials (levels 1, 2, and 4), the exponent of the normal force was close to zero and the cof was independent of the normal force. In the case of softer materials (levels 5–7), the cof was dependent on the normal force.

d was positive for all materials, and there were significant differences between harder materials (levels 1 and 2) and softer materials (levels 6 and 7). Under mica-lubricated conditions, the speed dependence of the cof was larger for soft materials. However, this speed dependence was smaller compared to that under dry conditions.

C. Results under TiO_2-lubricated conditions

For the softest material (level 7), a was larger than those for the other materials. For the other hardness levels, the cof exhibited negligible dependence on the material hardness under TiO_2-lubricated conditions.

b was negative and c was positive regardless of the material hardness, except for hardness level 4. The cof depended on the normal force for all hardness levels, in contrast to dry and mica-lubricated conditions, where it depended on the normal force only for softer materials.

The d value was small for all materials and there was no significant difference between materials.

V. Discussion

Under dry conditions, the cof was independent of the normal force when the artificial skins were harder than the finger pad. The adhesion friction between a finger and a plane is proportional to the real contact area A_r. During contact between a rough surface and a sphere, the real contact area is proportional to the normal force f_n due to the effects of surface asperities [23]. Furthermore, it is possible that the real contact area is proportional to the normal force even during contact between a finger and human skin due to the effects of fingerprints and obvious topographical features on the skin [10]. Therefore, the normal-force independence of the cof can be understood using the following equation:

$$\begin{aligned} \mu &= \frac{\tau A_r}{f_n} \\ &\propto \frac{\tau f_n}{f_n} \\ &= \tau, \end{aligned} \tag{6}$$

where the real contact area A_r is proportional to f_n; thus, the cof related to adhesion is constant. On the other hand, during complete contact between a finger and a surface that is as soft as or softer than the finger pad, the real and apparent contact areas almost coincide due to the small amount of interfacial water acting as an adhesive liquid bridge [13], [24]. Hence, for softer materials, (5) is valid and the cof depends on the normal force; i.e., it decreases as the normal force increases. As discussed above, the normal-force dependence of the cof depends on the material hardness. Specifically, when rubbing a soft surface with a finger, the normal-force dependence of the contact area should be considered, which is a phenomenon unique to pushing with a finger.

Under TiO_2-lubricated conditions, the cof depended on the normal force regardless of the material hardness, unlike under dry conditions. This may be because fine particles of TiO_2 adhere to the finger or the artificial skin model and fill the grooves; therefore, the real contact area might coincide with the apparent contact area even when the object is hard. Hence, the true contact area would change in proportion to the power of the normal force, as shown in Fig. 2, and the cof would depend on the normal force according to (5).

Under mica-lubricated conditions, the cof was independent of the normal force for harder artificial skins (levels 1–4). Furthermore, unlike the above cases, the cof did not depend on the normal force

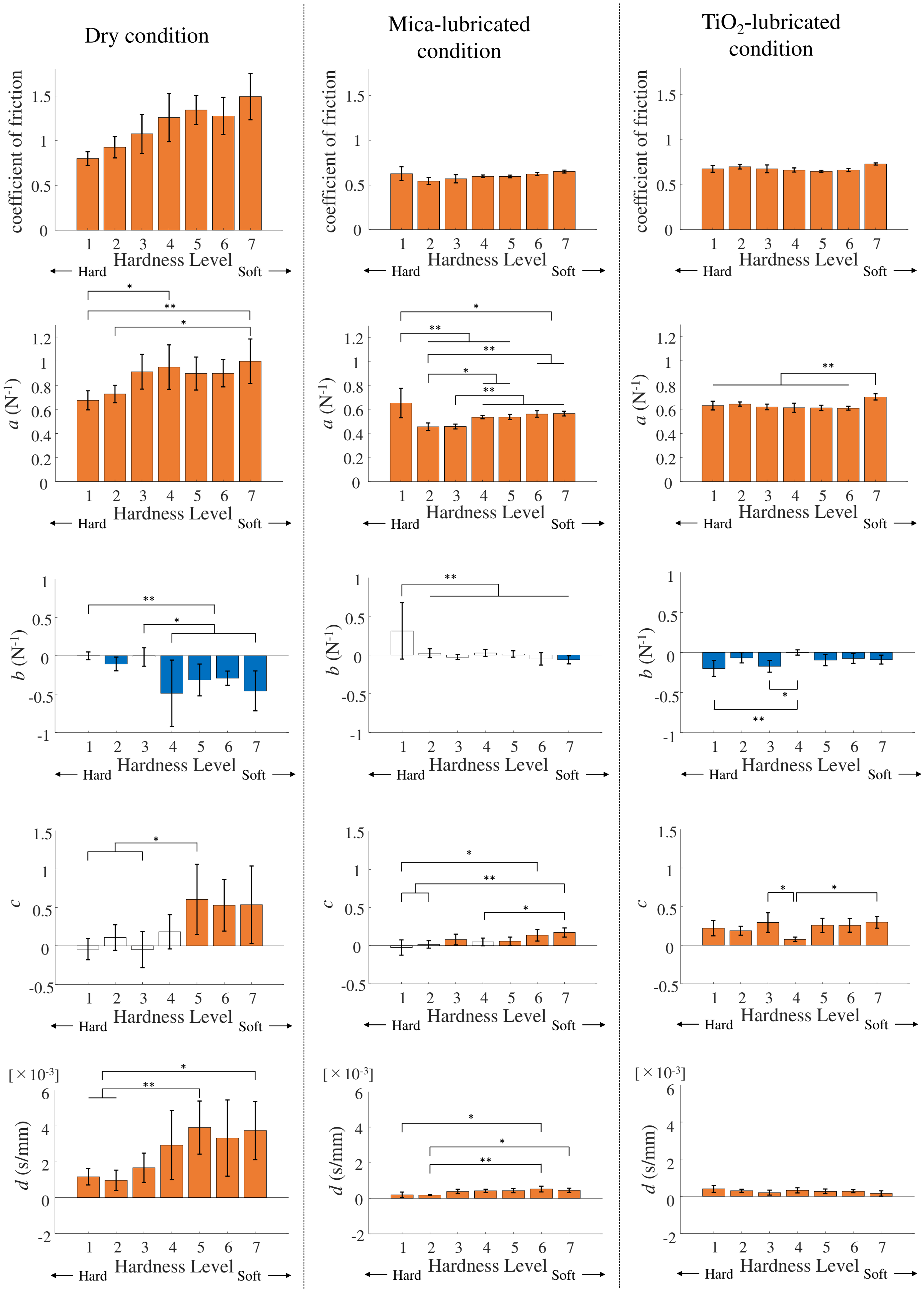

Fig. 7: Means and standard errors of cof, a, b, c, and d for each hardness level of the artificial skin model. The orange and blue bars are significantly positive and negative values tested by the t-test with $p < 0.05$, whereas the white bars are not statistically different from zero, *: $p < 0.05$, **: $p < 0.01$. Left, middle, and right columns represent dry, mica-lubricated, and TiO_2-lubricated conditions, respectively.

TABLE II: Cof when the normal force increases

	Material is harder than a finger	Material is softer than a finger
Dry	Constant	Decrease
Mica	Constant	Increase
TiO_2	Decrease	Decrease

and b was almost zero for softer artificial skins; b was negative only for the softest skin model (level 7). For the majority of hardness levels (levels 1–6), the exponents of the normal force were zero or positive. When the exponent is negative, adhesion friction is dominant; when the exponent is positive, deformation friction is dominant [14]. Hence, mica diminished the effect of adhesion friction, except for the softest material.

The above-mentioned tendencies are summarized as in Table II.

VI. Conclusions

Experiments were conducted to determine the effects of material hardness on the friction between a human finger and artificial skin model. Under dry conditions, when the artificial skin model was harder than a finger, the cof did not depend on the normal force. Conversely, when the skin model was as soft as, or softer than a finger, the cof decreased with increasing normal force. When the surface was lubricated with mica, which reduces friction, the cof again depended on the normal force for softer materials. This dependency was mainly caused by the deformation friction, whereby the cof increases as the normal force increases. Under TiO_2-lubricated conditions, normal-force dependence was observed even with harder materials. These differences in normal-force dependence might be due to the lubrication conditions affecting the real contact area or the dominant friction system. The hardness dependence of the cof varies according to the surface conditions. Therefore, the relationship between the apparent contact area and the normal force should be considered when determining the friction experienced by a finger touching soft materials, especially when the materials are softer than the finger. Furthermore, even when the material is harder than the finger, it should be considered depending on the lubrication conditions. These findings may provide insights into the friction experienced by a finger rubbing a soft surface such as skin and advance the design of products such as assistive robots involving human-robot body contact as well as skin care and cosmetic products.

References

[1] A. F. El-Shimi, “In vivo skin friction measurements,” *Journal Society Cosmetic Chemist*, vol. 28, no. 2, pp. 37–51, 1977.

[2] R. K. Sivamani, J. Goodman, N. V. Gitis, and H. I. Maibach, “Friction coefficient of skin in real-time,” *Skin Research and Technology*, vol. 9, no. 3, pp. 235–239, 2003.

[3] A. A. Koudine, M. Barquins, P. Anthoine, L. Aubert, and J. L. Lévêque, “Frictional properties of skin: Proposal of a new approach,” *International Journal of Cosmetic Science*, vol. 22, no. 1, pp. 11–20, 2000.

[4] M. Zhang and A. F. T. Mak, “In vivo friction properties of human skin,” *Prosthetics and Orthotics International*, vol. 23, no. 2, pp. 135–141, 1999.

[5] R. Fagiani, F. Massi, E. Chatelet, J. P. Costes, and Y. Berthier, “Contact of a finger on rigid surfaces and textiles: Friction coefficient and induced vibrations,” *Tribology Letters*, vol. 48, no. 2, pp. 145–158, 2012.

[6] K. Duvefelt, U. Olofsson, C. M. Johannesson, and L. Skedung, “Model for contact between finger and sinusoidal plane to evaluate adhesion and deformation component of friction,” *Tribology International*, vol. 96, pp. 389–394, 2016.

[7] W. Tang, S. rong Ge, H. Zhu, X. chuan Cao, and N. Li, “The influence of normal load and sliding speed on frictional properties of skin,” *Journal of Bionic Engineering*, vol. 5, no. 1, pp. 33–38, 2008.

[8] P. F. D. Naylor, “The skin surface and friction,” *British Journal Dermatology*, vol. 67, no. 7, pp. 239–248, 1955.

[9] M. Egawa, M. Oguri, T. Hirao, M. Takahashi, and M. Miyakawa, “The evaluation of skin friction using a frictional feel analyzer,” *Skin Research and Technology*, vol. 8, no. 1, pp. 41–51, 2002.

[10] M. J. Adams, B. J. Briscoe, and S. A. Johnson, “Friction and lubrication of human skin,” *Tribology Letters*, vol. 26, no. 3, pp. 239–253, 2007.

[11] B. Dzidek, M. J. Adams, Z. Zhang, S. Johnson, S. Bochereau, and V. Hayward, “Role of occlusion in non-coulombic slip of the finger pad,” in *Haptics: Neuroscience, Devices, Modeling, and Applications*, 2014, pp. 109–116.

[12] S. Derler, L.-C. Gerhardt, A. Lenz, E. Bertaux, and M. Hadad, “Friction of human skin against smooth and rough glass as a function of the contact pressure,” *Tribology International*, vol. 42, pp. 1565–1574, 2009.

[13] S. E. Tomlinson, R. Lewis, X. Liu, C. Texier, and M. Carré, “Understanding the friction mechanisms between the human finger and flat contacting surfaces in moist conditions,” *Tribology Letters*, vol. 41, no. 1, pp. 283–294, 2011.

[14] D. Mahdi, A. Riches, M. Gester, J. Yeomans, and P. Smith, “Rolling and sliding: Separation of adhesion and deformation friction and their relative contribution to total friction,” *Tribology International*, vol. 89, pp. 128–134, 2015.

[15] Y. Fujii, S. Okamoto, and Y. Yamada, “Friction model of fingertip sliding over wavy surface for friction-variable tactile feedback panel,” *Advanced Robotics*, vol. 30, no. 20, pp. 1341–1353, 2016.

[16] X. Liu, M. Carré, Q. Zhang, Z. Lu, S. Matcher, and R. Lewis, “Measuring contact area in a sliding human finger-pad contact,” *Skin Research and Technology*, vol. 24, no. 1, pp. 31–44, 2018.

[17] J. van Kuilenburg, M. A. Masen, and E. van der Heide, “A review of fingerpad contact mechanics and friction and how this affects tactile perception,” *Proceedings of the Institution of Mechanical Engineers Part J: Journal of Engineering Tribology*, vol. 229, no. 3, pp. 243–258, 2015.

[18] M. J. Adams, S. A. Johnson, P. Lefèvre, V. Lévesque, V. Hayward, T. André, and J.-L. Thonnard, “Finger pad friction and its role in grip and touch,” *Journal of The Royal Society Interface*, vol. 10, no. 80, p. 20120467, 2013.

[19] A. Imaizumi, S. Okamoto, and Y. Yamada, “Friction perception resulting from laterally vibrotactile stimuli,” *Robomech Journal*, vol. 4, no. 1, p. 12, 2017.

[20] H. Hasegawa, S. Okamoto, E. Hatem, and Y. Yamada, “Stochastic relationships between the normal and shear interaction forces during tactile exploration of textures,” in *Proceedings of IEEE International Conference on Systems, Man, and Cybernetics*, 2018, pp. 3033–3038.

[21] R. Shimizu and Y. Nonomura, “Preparation of artificial skin that mimics human skin surface and mechanical properties,” *Journal of Oleo Science*, vol. 67, no. 1, pp. 47–54, 2018.

[22] Y. Tanaka, W. M. Bergmann Tiest, A. M. L. Kappers, and A. Sano, “Contact force and scanning velocity during active roughness perception,” *Plos One*, vol. 9, no. 3, p. e93363, 2014.

[23] J. A. Greenwood and J. H. Tripp, “The elastic contact of rough spheres,” *Journal of Applied Mechanism*, vol. 34, no. 1, pp. 153–159, 1967.

[24] S. Derler and L.-C. Gerhardt, “Tribology of skin: Review and analysis of experimental results for the friction coefficient of human skin,” *Tribology Letters*, vol. 45, no. 1, pp. 1–27, 2012.