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Less Frictional Skin Feels Softer in a Tribologically Paradoxical Manner

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ABSTRACT In general, the friction coefficient of a soft object, which has a low elastic modulus, is greater than that of a hard object. Briefly, friction and hardness are physically correlated. Given this relationship, a question naturally arises: are they perceptually coupled? We hypothesized that the higher an object's surface friction coefficient, the softer it would feel in a physically consistent manner. To confirm this hypothesis, we conducted two types of psychophysical experiments using skin-like materials made of polyurethane and human cheeks as stimuli considering the potential applications in cosmetics. In experiment 1, skin-like objects with the same dimensions and stiffness were coated with powders so that they had different friction coefficients. Participants actively explored and evaluated the softness of these surfaces using their fingers. Their exploratory motions were restricted to either pressing or rubbing. When participants repeatedly pressed the surfaces with no sliding motion, they judged the softness of all the surfaces to be equal. In contrast, when participants rubbed the surfaces, they judged the surfaces with lower friction (i.e., more slippery) as softer than the surfaces with higher friction. In experiment 2, the same results were obtained using human cheeks, one side of which was lubricated to be more frictional. This psychophysical interference between hardness and friction is paradoxical in terms of tribology and contact mechanics. We discuss the potential reasons that led to these results.

INDEX TERMS Cheek, friction, hardness, lubrication, polyurethane, softness perception.

I. INTRODUCTION

The tactile sensations of daily products are designed to satisfy the needs of consumers. It is important to know the psychophysical relationship between the physical parameters of the products or materials and the tactile perception to achieve consumer satisfaction. Various studies have been conducted for such purposes [1]–[5]. We focus on the softness perception of human skin and objects as soft as human skin.

Although haptic softness can be defined in terms of various aspects including furry, granulous, viscoelastic, and deformable softness [6], most previous studies in this field have conducted psychophysical experiments in which elastic or deformable materials were pressed without sliding motions or pinched by fingers or tools [7]–[16]. For example, the roles of cutaneous and proprioceptive cues have been discussed, and the former is a dominant or satisfactory cue for the perception of deformable objects' softness [7], [9], [10]. Furthermore, softness perception by pressing or pinching relies on both the stiffness, i.e., spring constant, and elastic modulus, i.e., Young's modulus, of specimens [10], [11], [17]. The deformation of fingertip and object collectively determined by multiple types of hardness quantities potentially contributes to softness judgment [18]. Recently, the meaning of repetitive explorative motion, i.e., pressing, to judge softness has been discussed [16]. Nonetheless, humans also feel softness when rubbing surfaces [5], [6], [19]. Although friction occurs through rubbing objects, previous studies on perceptual dimensions for tactile material perception have shown that perceived softness and perceived friction are mostly independent [1], [20]–[24]. The perceptual dimension of softness and friction, i.e., stickiness/slipperiness and moistness/dryness, are judged differently, indicating that frictional properties such as the friction coefficient are considered to have little or no effect on the softness perception

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TABLE 1. Coefficient of friction of powdery surfaces.

Condition	A	B	C	D	E
Powder	Boron nitride	Mica	No powder	Titanium oxide (0.25 μm)	Titanium oxide (0.03 μm)
Applied amount (mg)	3.0	3.0	-	3.5	1.5
Coefficient of friction (-)	.40	.56	.86	1.00	1.11

or that their effect is relatively small compared with that of hardness.

Physically, the contact theory indicates that the friction coefficient depends on the elastic modulus of an object: the lower the elastic modulus, the greater the friction [25]–[27]. Briefly, a softer object yields a greater contact area, resulting in greater adhesion friction. As a result, the friction coefficient is approximately proportional to $-2/3$ the power of Young's modulus of a soft object. Further, the softer object deforms more and leads to greater internal friction or damping effects, referred to as hysteresis friction, which is approximately proportional to $-1/3$ the power of Young's modulus of a soft object. Thus, the friction coefficient and elastic modulus are negatively correlated (see section IV about the further connection between Young's modulus, friction, and softness perception). Our question is whether this relationship is also true between the friction and the softness perception of an object. More specifically, do surfaces with higher friction feel softer even when the elastic moduli of the objects are identical?

Several studies indirectly suggested this possibility. For example, Egawa *et al.* [28] investigated the correlation between physical friction on the skin of the contralateral volar forearm after applying emulsions and sensory evaluations during the application of emulsions on facial skin and found a weak correlation between physical friction and perceived softness. Takahashi *et al.* [29] investigated the relationship between several physical parameters, including frictional parameters and perceived softness, using five soft sponges composed of polyester urethane foam. Their results demonstrated that the sponges with higher friction were judged as softer. Nonetheless, they did not control either the friction or hardness of the objects being manipulated. Horiuchi *et al.* [30] investigated the relationship between the friction of powders on silicone rubber surfaces and the perceived softness of the powders on human skin; this relationship exhibited a positive correlation. However, the assessors, who were cosmetic professionals, might have judged the softness of powders on the skin, considering that cosmetics do not immediately change the skin stiffness. Hence, earlier studies have not investigated the relationship between physical friction and softness perception on the skin or on skin-like materials in which the lubrication conditions were manipulated, and the hardness was controlled.

To investigate whether physical friction influences softness perception, in this study, we conducted two types of psychophysical experiments. In the first experiment, participants either rubbed or pressed soft polyurethane surfaces, i.e., artificial skins, made using the same polyurethane formulation and the same molding process. However, these surfaces were covered with different lubricant powders so that they exhibited different friction coefficients. Participants discriminated perceived softness; we then investigated whether the friction would affect their perception of softness. In the second experiment, a protocol similar to the first experiment was adopted for human cheek skin. Note that the potential applications of the present study include cosmetic products, and then we target skin-like materials and human cheeks.

II. MATERIALS AND METHODS

The following experimental protocol was approved by the institutional review board of Shiseido Co. Ltd. (approval C01724 and C01931).

A. EXPERIMENT 1: SKIN MODEL

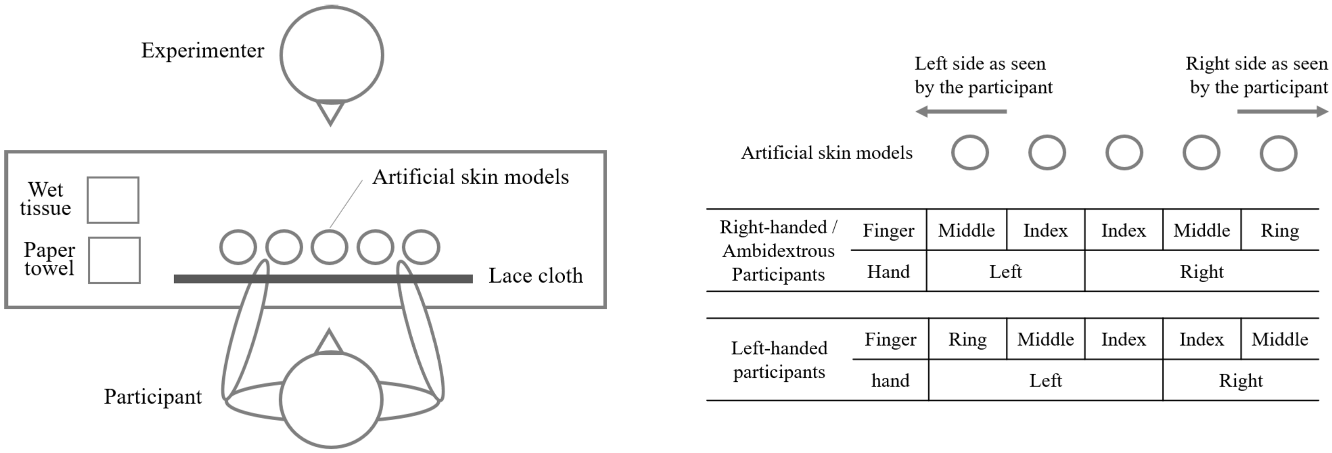
1) STIMULI

We used cylindrically artificial polyurethane skin (tailored based on existing products, Beaulax Co., Ltd, Saitama, Japan) with a diameter and thickness of 50 mm and 15 mm, respectively, and the surface roughness transferred from a Japanese female cheek. The hardness was designed to be similar to that of human facial flesh, with a hardness value of AO 4.5 (30.7 kPa in Young's modulus) measured using a durometer (GS-721, Teclock, Nagano, Japan) in accordance with ISO 7619-1.

We adopted five types of lubrication conditions using powders. In each of the four conditions, boron nitride, mica, titanium oxide (particle diameter: 0.25 μm), and titanium oxide (particle diameter: 0.03 μm, hydrophobic powder). These are popular cosmetic ingredients. In the fifth condition, no lubrication was applied. The amount of each type of powder was adjusted such that the surface was uniformly covered using a cosmetic brush. It should be noted that the lubrication powders do not influence the physical hardness of the artificial skins. The kinetic friction coefficient between the fingers and the surface was measured using an instrument described in [31] for each lubrication condition. Table 1 lists the measured values.

2) PARTICIPANTS

We recruited thirty-nine Japanese females (age: 20–68 years, native Japanese speakers), eleven American females (age: 28–62 years, native English speakers), and eleven Italian females (age: 26–44 years, native Italian speakers). All participants had lived in their native countries for more than ten years until the age of twenty years and were living in



Right-handed / Ambidextrous Participants	Finger	Middle	Index	Index	Middle	Ring
	Hand	Left		Right		

Left-handed participants	Finger	Ring	Middle	Index	Index	Middle
	hand	Left			Right	

(a) Experiment 1 setup

(b) Fingers touching each artificial skin model in experiment 1

FIGURE 1. Experiment 1: Setup using five different lubrication methods in polyurethane samples.

Japan at the time of the experiments. None of the participants reported any sensory, cutaneous, or kinetic impairments. We recruited participants irrespective of their handedness. Written informed consent was obtained from all participants.

3) RANKING TASKS

Firstly, each participant conducted ranking tasks of five specimens for each evaluation descriptor, i.e., softness and friction during rubbing. The tasks for judging softness and friction were conducted separately in randomized order. After that, they did another ranking task of five specimens for softness during pressing. Here, pressing is an indentation perpendicular to the surface without sliding motion and intentional exertion of shearing forces. For individuals, three tasks, i.e., softness and friction judgment during rubbing and softness judgment during pressing, were conducted only once. All participants completed each task within 4 min.

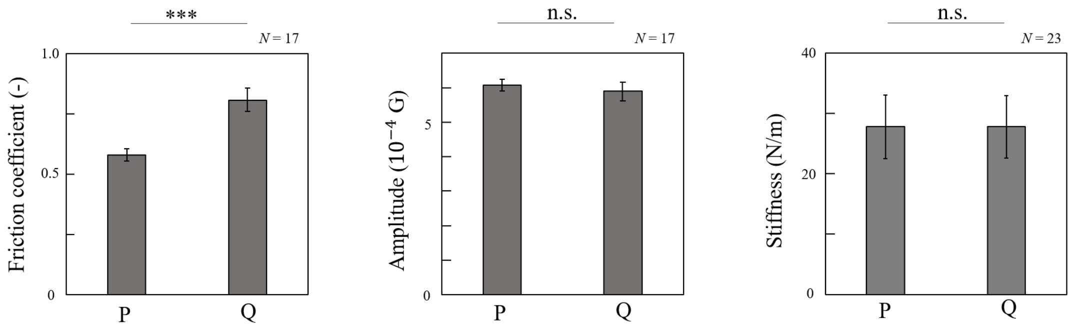
Fig. 1 (a) shows the experimental setup for the psychophysical experiments. A lace cloth was placed between the participant and the five types of stimuli to prevent them from judging the stimulus conditions based on the visual assessment of the surface, because one type of powder looked slightly white on the artificial skin. Nonetheless, the participant was made aware of the location of the stimuli. The experimenter randomly placed the five types of stimuli in front of participants in each trial. As shown in Fig. 1 (b), the participant touched the five types of stimuli using different fingers in a way that the lubrication powders were not mixed. Zoeller *et al.* [13] showed that the sensitivity is different among fingers during pressing objects. Therefore, we checked whether the fingers used in Experiment 1 exhibited biases of ranks during the rubbing task, and the Friedman test did not reveal differences among the fingers during rubbing in perceived softness ($N = 61, p = 0.112, \chi^2 = 7.5, df = 4$) and in perceived friction ($N = 61$, $p = 0.165$, $\chi^2 = 6.5$, $df = 4$). There was no bias introduced by the specific fingers used in the study, i.e., no finger effect on the softness ranks in the following tasks.

TABLE 2. Descriptions that mean soft or friction.

Description	Japanese	English	Italian
Soft	*Yawarakai*	*Soft*	*Morbida*
Frictional	*Masatsu-kan*	*Friction*	*Frizone*

The participants were presented with all types of stimuli simultaneously and asked to rub each surface. They then ranked the stimuli based on each of the two perceptual descriptions: softness and friction, presented in their own native languages, as shown in Table 2. "Yawarakai," which means soft in Japanese, does not have the meaning of smoothness [32]. Inversely, "soft" in English and "morbida", which means soft in Italian, include the meaning of smooth [33], [34]. We just focused on the softness perception and then presented the definition of the description to the participants highlighting that the definition of "soft" and "morbida" did not have the meaning of smoothness. Specifically, softness was defined as follows: not hard, firm, or stiff, but easy to press and deform; soft was therefore regarded as the opposite of hard. Here, softness largely corresponds to physical elasticity but does not include the nuance of surface uniformity, unlike in a previous study [35]. Hence, the softness defined here corresponds to the deformability among multiple types of softness [6]. Friction was defined as the feeling of a force that prevents one surface from sliding easily over another surface. High friction is the opposite of low friction. The participants did not have any difficulty understanding these definitions. The experimenter instructed participants as follows: "rank the five specimens in order of 'softness/friction' feeling when you rub your finger on the surface."

The order of the two descriptors used for ranking was randomized for each individual. The participants ranked the one of the descriptors after rubbing all five stimuli. They



(a) Friction (b) Vibration (c) Stiffness

FIGURE 2. **Friction coefficient, vibration, and stiffness of the stimuli (cheeks with powders) of experiment 2 measured by three original sensors, which were customized to measure the physical conditions of human cheek skin. Bars indicate the arithmetic mean of the friction coefficient, mean amplitude spectrum (0.56–1000Hz), and stiffness, respectively. Error bars indicate the standard error. n.s. and *** denote $p \geq 0.05$ and $p < 0.001$, respectively.**

rubbed them until they could assess. After assigning ranks to the stimuli in terms of the first descriptor, the participants' fingers were wiped using wet papers and air-dried for five minutes. The five types of stimuli were then randomly repositioned, and the participants assessed the stimuli using the next perceptual descriptor. For each participant, the ranking tasks were conducted only once for each of the two descriptors.

After these tasks, the fingers were cleaned and dried again. The participants pressed the five types of rearranged stimuli without sliding the fingers on the surface and ranked them based on perceived softness, during which the rubbing motion was prohibited.

During the experiments, the finger motions of the participants were monitored by the experimenter, who gave instructions to the participants if needed. Before the experiments, participants washed their hands using warm water and soap and waited for ten minutes in a room with stable humidity (45–55%) and temperature (22–23^{o}C). The participants' fingers were then wiped using wet paper cloths and air-dried for five minutes before each task.

4) STATISTICAL ANALYSIS

We applied the Freidman test to the ranks of five skin models for each descriptor as an omnibus test to investigate potential differences among the stimuli. Pair-wise comparisons were then conducted as a post-hoc test to identify the surfaces responsible for the differences with a Bonferroni correction. We also calculated the Spearman's rank correlation coefficient between the ranks of friction and softness provided by participants in the rubbing trials. Statistical analyses were conducted using SPSS Statistics (version 23, IBM Corp., Chicago, IL).

B. EXPERIMENT 2: HUMAN CHEEK

1) STIMULI

We used two types of loose powder formulations designated as formulae P and Q, as shown in Table 3. The formulations were adjusted so that they exhibited different lubrication properties and complied with the internal safety regulations. Formula P or Q was applied on each cheek of participants. It is noted that no dry condition was tested as a control condition. The vibration and friction caused when stroking the cheek by a contactor were measured using the tactile sensor developed as in [36], [37]. The stiffness of the cheek was measured using a force-displacement sensor [38]. Fig. 2 summarizes the measurement results. The friction coefficient was lower for formula P than for formula Q. On the other hand, there were no significant differences between formulae P and Q in terms of vibratory amplitude and stiffness. Thus, formulae P and Q differed in terms of friction but not in terms of stiffness and surface roughness on the cheek. As mentioned below, these two types of powder were placed on the cheeks of participants and they examined their own cheeks. In order to control the stimuli, the same person could have provided his/her own cheeks to be examined by participants. However, in this case, this provider has to wash the face many times, leading to skin damages. Hence, we adopted a method where participants touched their own cheeks.

TABLE 3. **Formulations of the two loose powders in percentage.**

Ingredient		Formula P (low friction)	Formula Q (high friction)
Talc		70.8	70.8
Boron nitride		29	-
Titanium oxide (particle diameter: 0.03 μm)	A	-	18
	B	-	11
Preservative		0.2	0.2

2) APPLICATION OF LOOSE POWDERS ON CHEEKS

Participants removed their makeup using a makeup remover and washed their face and hands using warm water and soap. They then waited for 10 min in a room with stable humidity (45–55%) and temperature (22–23^{o}C). The participants' fingers were wiped using wet paper cloths and air-dried for five min before each task. As aforementioned, participants then had the moisturizer (Vital Perfection Uplifting and Firming Cream Enriched, Shiseido Co., Ltd., Tokyo, Japan, 200 μL) applied on their whole face by an experimenter and waited for 15 min. The moisturizer was used to adjust the individual skin conditions and apply the loose powders equally across the participants. After that, an experimenter applied each type of loose powder (30 mg) using a sponge puff (114, Shiseido Co., Ltd., Tokyo, Japan) randomly on either of the cheeks. For example, if formulation P was applied on the right cheek, then formulation Q was applied on the left cheek.

3) PARTICIPANTS

We recruited twenty-five participants, nine Japanese females (age: 23–66 years, native Japanese speakers), nine American females (age: 23–62 years, native English speakers), and seven Italian females (age: 26–53 years, native Italian speakers). All participants had lived in their native countries for more than ten years until the age of twenty years old and were living in Japan as of the date of the experiments. None of them reported any sensory, cutaneous, or kinetic impairments. We recruited them irrespective of their handedness. Written informed consent was obtained from each participant. Two American participants were excluded from the analysis because of cosmetic pilling of the skin while rubbing their cheek in each trial. We investigated all participants as a single group.

4) TASKS

The participants were asked to rub the surfaces of their right and left cheeks using both index fingers simultaneously. The right index finger rubbed the right cheek, and the left index finger rubbed the left cheek. They were then asked which side felt softer and which more frictional. The order of these two questions, that is, softness and friction, was randomized. The two perceptual descriptions (softness and friction) were the same as in Experiment 1. A mirror was not used; the participants explored their cheeks without looking at their faces and behaviors. After these tasks, participants pressed both sides of their cheeks without sliding their fingers and answered which side felt softer. During the experiments, the finger motions of the participants were monitored by the experimenter, similarly, to Experiment 1. All participants completed the task within 1 min.

5) STATISTICAL ANALYSIS

We applied a binomial test to the results of each descriptor to investigate potential differences between stimuli. Statistical analysis was conducted using SPSS Statistics, as in Experiment 1.

III. RESULTS

A. EXPERIMENT 1: SKIN MODEL

Fig. 3 shows the results of the experiments using artificial skin as stimuli. The horizontal axis indicates the lubrication condition (A: boron nitride, B: mica, C: no lubricant, D: titanium oxide (particle diameter: 0.25 μm), and E: titanium oxide (particle diameter: 0.03 μm)). The vertical axis is the rank of softness or friction perceived by rubbing or softness perceived by pressing.

TABLE 4. Test results of between-stimuli softness and friction comparison in experiment 1.

	p	χ^2	df
Softness felt during rubbing	< 0.001	69.59	4
Friction felt during rubbing	< 0.001	68.35	4
Softness felt during pressing	0.153	6.70	4

TABLE 5. Results of softness and friction comparisons between lubrication conditions in experiment 1.

(A) Softness felt during rubbing

	T_{neg}	T_{pos}	z	p	r
A vs B	547.5	1343.5	-2.940	.033*	.376
A vs C	405.5	1485.5	-3.963	.001**	.507
A vs D	174.5	1716.5	-5.598	<.001***	.717
A vs E	184.0	1707.0	-5.515	<.001***	.706
B vs D	354.0	1537.0	-4.304	<.001***	.551
B vs E	406.0	1485.0	-3.915	.001**	.501
C vs D	426.5	1464.5	-3.800	.001**	.487
C vs E	531.0	1360.0	-3.027	.025*	.388

(B) Friction felt during rubbing

	T_{neg}	T_{pos}	z	p	r
A vs D	1576.0	315.0	-4.576	<.001***	.586
A vs E	1658.0	233.0	-5.171	<.001***	.662
B vs D	1465.0	426.0	-3.766	.002**	.482
B vs E	1597.0	294.0	-4.730	<.001***	.606
C vs D	1376.5	514.5	-3.153	.016*	.404
C vs E	1625.0	266.0	-4.955	<.001***	.634

Result of Wilcoxon signed-rank test with Bonferroni adjustment, in Experiment 1. A: boron nitride, B: mica, C: no lubricant, D: titanium oxide (particle diameter: 0.25 μm), and E: titanium oxide (particle diameter: 0.03 μm). T_{neg}: sum of negative ranks, T_{pos}: sum of positive ranks, z: normalized sum of ranks. *, **, and *** denote $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively. r: effect size ($z/\sqrt{n}$).

Significant differences ($p < 0.05$) in the ranks were found among the lubrication conditions for the rubbing tasks, but not for the pressing tasks (Table 4). Hence, we performed the Wilcoxon signed-rank test as a post-hoc pair-wise test for all the pairs of rubbing task conditions (Table 5). Condition A was judged softer than conditions B, C, D, and E, and conditions B and C were also judged softer than conditions D and E. Condition D and E were judged to have higher friction than conditions A, B, and C.

To examine the link between perceived friction and softness during rubbing, we calculated Spearman's rank correlation coefficient between the ranks provided for friction and softness by all participants. The correlation coefficient was $r = -0.35$ ($p < 0.001$).

Although the conditions physically differed only in terms of surface friction, the perceived softness differed among the stimulus conditions during rubbing. The less frictional conditions were judged as softer than the more frictional conditions. These results opposed our hypothesis that surfaces with higher friction coefficients could feel softer, based on the law of contact mechanics.

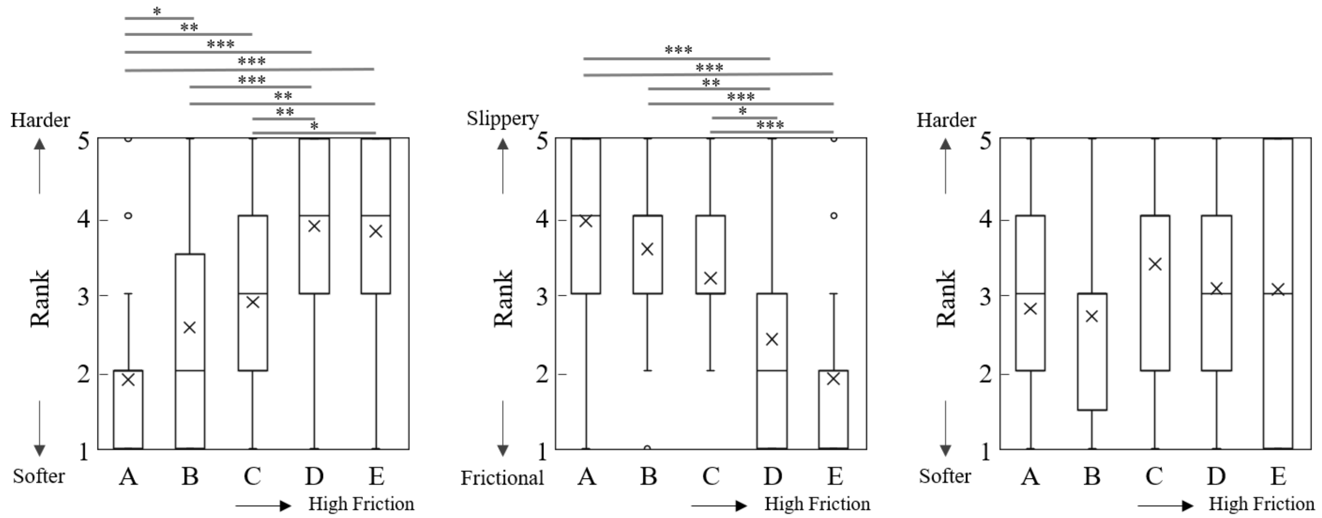


FIGURE 3. Result of experiment 1 using artificial skin models. *, **, and*** denote $p < 0.05$, $p < 0.01$, and $p < 0.001$ in the Wilcoxon signed-rank test with Bonferroni adjustment, respectively. A: boron nitride, B: mica, C: no lubricant, D: titanium oxide (particle diameter: 0.25 μm), and E: titanium oxide (particle diameter: 0.03 μm).

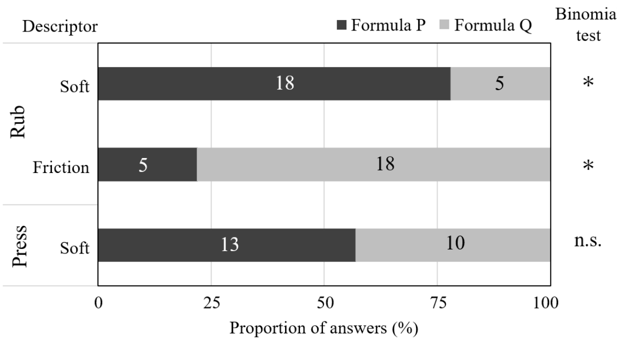


FIGURE 4. Results of experiment 2 during rubbing the cheeks with two types of loose powders. The numbers of responders for each formula are indicated on the bars. n.s. and * denote $p \geq 0.05$ and $p < 0.05$ with a binomial test, respectively.

B. EXPERIMENT 2: HUMAN CHEEK

Fig. 4 shows the proportion of answers to the question about which side of the cheeks felt softer or more frictional. Eighteen among the 23 participants judged the cheek with formula P to be softer ($p = 0.011$, $z = 2.50$, $N = 23$) and the cheek with formula Q to be more frictional ($p = 0.011$, $z = 2.50$, $N = 23$) while rubbing. In contrast, the proportions for formulae P and Q were almost tied in terms of the perceived softness felt during pressing ($p = 0.678$, $z = 0.42$, $N = 23$).

These results are consistent with those in Experiment 1 but disagree with our hypothesis introduced in Section I.

IV. DISCUSSION

Most previous studies of softness perception have focused on the compliance of objects during pressing or pinching [7]–[16]. However, humans also feel softness while rubbing surfaces [4], [6], [19]. As mentioned earlier, although friction occurs during rubbing objects, previous studies on the perceptual dimensions have shown that perceived softness and perceived friction are mostly independent [1], [20]–[24]. We investigated the hypothesis that surfaces with greater friction coefficients would feel softer considering the law of contact mechanics.

In the two experiments, participants judged the hardness perceived by rubbing several types of artificial skins or their own cheeks only when their surface lubrication was manipulated. Interestingly, the effect of friction was the opposite of that predicted by our hypothesis. The smaller the friction coefficient of the surface, the softer it felt. To the best of our knowledge, this is the first study to report that physical surface friction affects softness perception. As previously mentioned in Section I, earlier studies [28]–[30] did not directly investigate the effect of physical friction on the perception of softness. They did not control either the friction or hardness of objects while manipulating one of them [29] or only performed a sensory evaluation to characterize emulsions or powders themselves [28], [30]. Their objectives differed from those of the present study, in which participants rubbed and judged the softness under controlled conditions with the same hardness in the basal layer and only performed rubbing or pressing.

For the softness perception, the features of the contact between the object and fingertip are recognized as an important cue [7]–[11], [18], [39]–[43], based on which we have a hypothetical explanation of the present results. First, a hypothesis of softness perception is introduced. According to Hertz theory, when an elastic sphere contacts a plane with the normal force f_n, the contact area A is given as follows [44]:

$$A \propto \left(\frac{f_n\left(\frac{1-\nu_f^2}{E_f} + \frac{1-\nu_{obj}^2}{E_{obj}}\right)}{\frac{1}{R_f} + \frac{1}{R_{obj}}} \right)^{\frac{2}{3}} \qquad (1)$$

where R_f and R_{obj} are the radii of the sphere and flat object ($1/R_{obj} = 0$), respectively. The sphere corresponds to the fingertip and R_f is its size. E_f and E_{obj} are Young's moduli of the sphere and flat object, respectively. Provided that the sphere is a fingertip, E_f and R_f are known values. The formula suggests that E_{obj} can be estimated by f_n and A. The Poisson ratios ν_f and ν_{obj} are nearly constant, i.e., 0.5 [45], considering that the flat object is skin: $\nu_f \sim \nu_{obj} \sim 0.5$. Briefly, based on the ratio of A and f_n, the hardness of the object is estimated as follows:

$$\frac{A}{f_n^{\frac{2}{3}}} \propto \left(R_f\left(\frac{1}{E_f} + \frac{1}{E_{obj}}\right)\right)^{\frac{2}{3}}. \tag{2}$$

Although (1) and (2) mention the contact area, a similar discussion can be held for the maximum pressure or maximum normal deformation of the sphere.

When the sphere slides on a flat surface, a tangential force f_t is applied to the objects. If the components of the contact force, that is, f_t and f_n (normal force), are not perceptually precisely decoupled, which may be a strong assumption to be tested in the future, and the hardness perception is based on the ratio of the resultant contact force f_r and A, (2) can be replaced by:

$$\frac{A}{f_r^{\frac{2}{3}}} \propto \left(R_f\left(\frac{1}{E_f} + \frac{1}{E'_{obj}}\right)\right)^{\frac{2}{3}} \tag{3}$$

$$f_r = (f_n^2 + f_t^2)^{\frac{1}{2}}. \tag{4}$$

E'_{obj} is the perceived Young's modulus. By using Amontons-Coulomb's law ($f_t = \mu f_n$) and the coefficient of friction μ, (3) can be rewritten as

$$\frac{A}{f_n^{\frac{2}{3}}(1+\mu^2)^{\frac{1}{3}}} \propto \left(R_f\left(\frac{1}{E_f} + \frac{1}{E'_{obj}}\right)\right)^{\frac{2}{3}}. \tag{5}$$

This indicates that the left side rate decreases as μ increases, leading to an increase in E'_{obj}. Hence, the change in μ may interfere with the judgment of object hardness while rubbing it. The above discussions focused on the contact force and skin-object contact area; however, the confusion or incorrect separation of skin deformations caused by the normal and tangential forces may also explain the results of our experiment.

In Experiment 1, some participants reported that higher frictional conditions D and E were felt softer than lower frictional conditions A and B. This tendency was in contradiction to the average overall results. It is not clear whether they felt conditions D and E as softer than the others, or whether instead, they failed to distinguish perceived softness among the five types of stimuli and randomly made up their answers. The titanium oxide powder used in condition E is hydrophobic, while the others are not. Therefore, the skin water content or sweat of individual fingers might have affected the lubrication and their judgment of friction and softness. Further studies on the interaction between, for example, finger-sweat and powder characteristics are necessary.

Some questions remain unanswered about the perception of softness caused by the difference in friction coefficients. In this study, participants evaluated the feeling of softness when rubbing the surfaces of artificial skin models or their cheeks. It is not clear whether the same phenomenon is observed when rubbing objects with stiffness markedly different from human skin. Moreover, the stiffness of the stimuli in the experiments was the same, and we did not compare the difference in physical stiffness with the difference in perceived softness caused by friction. We did not conduct this comparison mainly because the surface friction is covaried with the object stiffness, and it is difficult to prepare a stimulus set with different stiffnesses but the same friction. Additionally, although the ranking task was adopted in Experiment 1, the psychophysical method of constant stimuli provides more solid results. However, the method of constant stimuli requires long task periods, which were not allowed under the pandemic situation. Previous studies have shown differences in attitudes and sensory perception toward cosmetic products among cultures [46]–[49]. For example, American people tend to rub their skins to judge its softness, whereas Japanese people opt to press [48]. We recruited Japanese, Italian, and American participants to our experiments and investigated cross-cultural differences. However, we could not conclude potential similarities or differences among different cultures mainly because of the limited number of participants from different cultures. Finally, we introduced a hypothetical principle of friction-driven softness perception; however, this principle needs to be pursued in the future. The present study merely demonstrated a relationship between the surface friction and softness perception when rubbing the skin and skin-like objects.

V. CONCLUSION

This work aimed to test the hypothesis that surface friction could influence the softness perceived when a finger rubs the surface of a soft material. We created controlled stimuli with equivalent stiffness and different friction coefficients on the surface using artificial skin and human cheeks. The artificial skin was covered with different kinds of lubricant powders, and the human cheeks were covered with loose powders made of cosmetic powder ingredients. We conducted two psychophysical experiments using artificial skin and human cheeks, where participants discriminated the softness of the stimuli during rubbing. The first experiment, using artificial skin, found that friction affected the perceived softness. This finding was replicated in the second experiment using human skin.

We conclude that surface friction affects the perception of softness when rubbing soft objects. This influence appears to be observed only when the surfaces were rubbed, but not when they were pressed. Interestingly, the effect of friction was the opposite to that predicted by our hypothesis. It was demonstrated that the smaller the surface friction coefficient, the softer the surface felt. We suspect that human's incorrect separation between the normal and tangential forces or skin deformations at the finger pad explains this phenomenon; however, the root cause of this phenomenon remains to be elucidated in the future.

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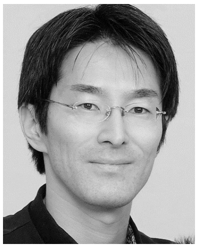

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