

# Skin quality sensor to evaluate vibration and friction generated when sliding over skins

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## Abstract

**Objective:** The mechanical condition and tactile evaluation of skin are essential for the development of skin care products. Most of the existing commercial instruments and studies aim to evaluate the skin surface by pressing it for hardness or by using imaging sensors, but there have been few instrumental measurements employing rubbing motion. Here, we have developed a sensor specialized for tactile sensation and the contact phenomenon during skin rubbing.

**Methods:** The developed sensor has three features: It can measure body parts including cheeks and arms, automate the rubbing motion of the probe and measure vibration and friction simultaneously. It is hand-held, with metal probes that rub the skin surface while rotating under a motor drive; it has an accelerometer and a force sensor beneath the probe measuring vibration and friction forces. To evaluate the validity of the sensor's measurements, artificial skin models were measured using the developed sensor and commercially available sensors and the results were compared. The relationship between the sensor output, surface roughness measurement and sensory evaluation was also investigated. Additionally, we evaluated the inter-rater reliability when measuring actual skin.

**Results:** The measurements of five artificial skin models with different surface shapes showed a high correlation ( $r=0.99$ ) between the vibration intensity values evaluated by the developed sensor and those measured by a tri-axial acceleration sensor attached to a fingernail. The correlation coefficient between the vibration intensity values and surface roughness was  $r=0.91$ , and the correlation with the sensory evaluation score of roughness was  $r=0.99$ . The friction coefficients measured by the developed sensor and the force plate had  $r=0.93$ , based on measurements of five artificial skin models with different friction conditions. The inter-rater correlation coefficients between the three participants of the developed sensor were as high as 0.92 and 0.94 for the vibration and friction measurements respectively.

**Conclusion:** The vibration intensities and friction coefficients from the sensor were highly correlated with those of the conventional sensor. The inter-rater

reliability was also high. The developed sensor can be useful for tactile evaluation in skin-care product development.

#### KEYWORDS

rubbing, sensory evaluation, skin physiology, skin structure, tactile sensation

#### Résumé

**Objectif:** l'état mécanique et l'évaluation tactile de la peau sont essentiels au développement de produits de soins de la peau. La plupart des instruments disponibles sur le marché et des études publiées à ce jour évaluent la surface de la peau en la comprimant pour déterminer sa dureté ou en utilisant des capteurs d'imagerie, mais il n'y a eu que peu de mesures instrumentales utilisant le mouvement de frottement. Ici, nous avons développé un capteur spécialisé pour la sensation tactile et le phénomène de contact lors du frottement de la peau.

**Méthodes:** le capteur développé possède trois caractéristiques : il permet d'exercer des mesures sur plusieurs parties du corps, y compris les joues et les bras ; il automatise le mouvement de frottement de la sonde et il mesure simultanément les vibrations et les frottements. Tenu à la main, doté de sondes en métal qui frottent la surface de la peau tout en tournant sous l'action d'un moteur, il est équipé d'un accéléromètre et d'un capteur de force situé sous la sonde qui mesure les forces de vibration et de frottement. Pour déterminer la validité des mesures du capteur, des modèles de peau artificielles ont été évalués à l'aide du capteur développé et de capteurs déjà disponibles sur le marché, et les résultats ont été comparés. Le lien entre les mesures réalisées à l'aide du capteur, la mesure de la rugosité de la surface de la peau et l'évaluation sensorielle a également été étudié. En outre, nous avons évalué la fiabilité inter-évaluateurs lors de la mesure réelle de la peau.

**Résultats:** les mesures de cinq modèles de peau artificielle avec des formes de surface différentes ont montré une forte corrélation ( $r = 0,99$ ) entre les valeurs d'intensité des vibrations évaluées par le capteur développé et celles mesurées par un capteur d'accélération triaxial fixé à un ongle. Le coefficient de corrélation entre les valeurs d'intensité des vibrations et la rugosité de la surface était  $r = 0,91$ , et la corrélation avec le score d'évaluation sensorielle de la rugosité était  $r = 0,99$ . Les coefficients de frottement mesurés par le capteur développé et la plaque de force étaient  $r = 0,93$ , sur la base des mesures de cinq modèles de peau artificielle avec des conditions de frottement différentes. Les coefficients de corrélation inter-évaluateurs entre les trois participants utilisant le capteur développé ont atteint 0,92 et 0,94 pour les mesures de vibrations et de frottement, respectivement.

**Conclusion:** les intensités des vibrations et les coefficients de frottement du capteur se sont avérés fortement corrélés avec ceux du capteur conventionnel. La fiabilité inter-évaluateurs était également élevée. Le capteur développé peut être utile pour l'évaluation tactile lors du développement de produits de soins de la peau.

## INTRODUCTION

Evaluation of skin mechanical condition and tactile sensation is essential in the development of skin-care products. Sensory evaluation and instrumental measurement are used together for such purposes [1, 2]. Sensory evaluation by experts enables direct evaluation of tactile sensations felt by humans and analytic assessment of the differences between products, while evaluation by consumers enables evaluation of preferences under conditions closer to reality. However, the resolution of sensory evaluation is lower than that of instrumental measurement, and the training and evaluation costs are higher. Nevertheless, the number of physical quantities that can be measured with a single device is limited.

The main movements used by humans to evaluate skin tactile sensation are pushing and rubbing motions [3]. However, most of the commercially available skin measurement devices employ noncontact measurement or pushing and sucking motions and do not involve rubbing [4–6], while this study focuses on the rubbing motion. Judgement of surface quality by tactile sensation consists of at least five dimensions: micro-roughness, macro-roughness, hardness/softness, friction and warmth/coolness [7, 8]. These dimensions are also considered common in judging the tactile texture of the skin. When a human finger slides across the skin, the main purpose is to judge the micro-roughness and friction. To judge the micro-roughness of a surface, humans rely on the vibration information generated when they rub their fingers on the surface [9]. Therefore, this study focuses on the vibration and frictional forces related to the texture of the cosmetic formulation and the tactile sensation of the skin, as evaluated by the rubbing motion.

Rheological and tribological measurements are used to evaluate the texture of cosmetic formulations and tactile sensation of skin [2, 10–18]. Rheological measurements evaluate the viscoelastic properties of cosmetic formulations under shear deformation, while tribological measurements evaluate the lubrication state of skin and friction properties of the formulation. However, measuring actual skin using these devices is difficult. Egawa et al. attached a special jig to a friction measurement device called KES and evaluated the texture of the skin-care product applied to the inner forearm and the tactile sensation of bare skin [18]. However, there were restrictions on the measurement site, and facial skin was not measured. In contrast, hand-held instruments that can measure the frictional properties of skin on surfaces, such as the face, have been studied and are commercially available [19, 20]. However, these instruments do not aim to measure vibrations.

Sensors have been developed that can be attached to a finger and the generated vibrations can be measured when the finger rubs a surface [21, 22]. The sensor developed by Nakatani et al. measures contact force from the amount of deformation of the finger and can simultaneously measure finger vibration with an accelerometer [22]. However, these devices were not designed to simultaneously measure vibration and friction. Although the measurement of the phenomenon when a user rubs the skin with a finger is useful for recording the tactile experience, including human exploratory hand motion, making a highly reproducible measurement would be difficult because the states of the finger and the hand motion change. For the purpose of using instrumental measurement in the development of cosmetics, it is desirable to obtain highly reproducible information on the skin. Based on this background, this study aimed to develop a sensor specialized for tactile skin evaluation in cosmetics development and defined the following design requirements:

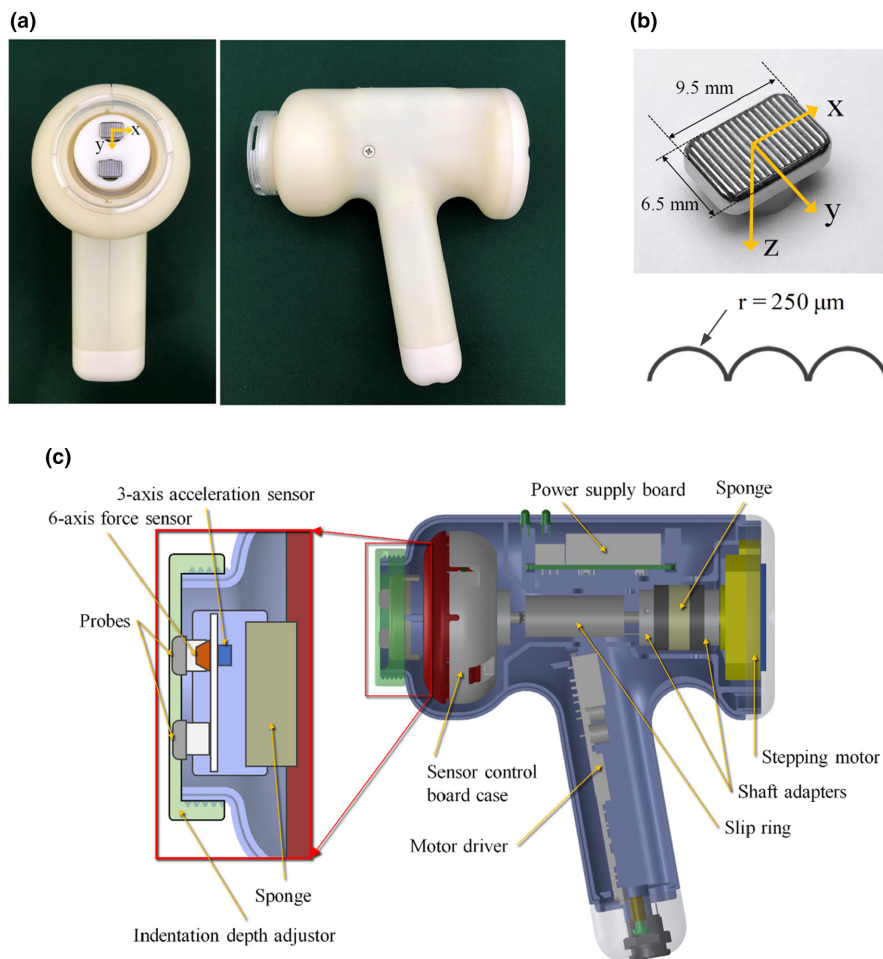
- Applicability to various parts of the body (face, inner forearm, etc.)
- Simultaneous measurement of the vibration and friction generated when skin is rubbed.
- Automation of the rubbing motion to improve reproducibility of the measurement results.

This paper reports on the configuration of the developed sensor and the validity of the sensor based on controlled artificial skin models and experiments on real skin.

## METHODS

### Development of a tactile sensor

The configuration of the developed sensor is shown in Figure 1a. The sensor measures the vibration and the contact force generated when the probe rubs on the skin. In order to secure a sufficient rubbing distance even in a narrow area, the probe is set to rotate, with a rotation radius of 7.35 mm and a rotation direction of  $x$ . The two probes were mounted symmetrically around the centre of rotation to stabilize the rotational motion of the probe. The surface shape of the probe was based on the surface shape of probes used in fabric texture evaluation equipment (Figure 1b) [18]. The probe size was 6.5 × 9.5 mm. Figure 1c shows the internal configuration of the sensor. The housing of the sensor was designed to be graspable. A six-axis force sensor (S10S1-WM155-K1-P5A, Touchence Inc.) and a three-axis acceleration sensor (LIS344ALH, STMicroelectronics) were placed directly under one of the two probes. The measurement range of the force sensor



**FIGURE 1** Developed sensor. (a) Photograph of the sensor. (b) Probe made of stainless steel that imitates the surface shape of a fingerprint. The cross section indicates a series of semi-cylinders with a radius of  $250 \mu\text{m}$ . (c) Internal structure of the sensor. The right figure shows the overall structure of the sensor, and the left figure shows the structure of the tip of the sensor.

was  $-4$  to  $4 \text{ N}$  for  $F_x$  and  $0$ – $10 \text{ N}$  for  $F_z$ . Since the AD conversion was 12 bit, the designed resolutions of  $F_x$  and  $F_z$  for the sensor were  $1.95$  and  $2.44 \text{ mN}$  respectively. However, the standard deviations of  $F_x$  and  $F_z$  in the no-load condition were  $5$  and  $7 \text{ mN}$  respectively. Thus, the minimum detectable values were  $10$  and  $14 \text{ mN}$  for  $F_x$  and  $F_z$ , respectively, assuming twice the standard deviation in the no-load condition. The nonlinearities of  $F_x$  and  $F_z$  were  $\pm 2.4\%$  F.S. and  $\pm 3.3\%$  F.S. respectively. The measurement range of the accelerometer was  $-2$  to  $2 \text{ G}$  in each axis, and since the AD conversion was 12 bit, the designed resolution was  $0.98 \text{ mG}$ . However, the standard deviation of the sensor readings at rest was  $1.98 \text{ mG}$ , and the minimum detectable value was  $4 \text{ mG}$ , which was twice the standard deviation at rest. The nonlinearity of each direction was  $\pm 0.5\%$  F.S. The outputs of the two sensors were recorded synchronously. The sampling frequency of the sensors was set to  $2000 \text{ Hz}$  in order to evaluate vibrations in the high-frequency range that humans can perceive. The tip of the sensor housing was equipped with a push-in depth adjuster, which kept the contact force between the probe and the skin in the normal direction approximately constant ( $0.2$ – $0.4 \text{ N}$ ), regardless of the user. The probe rotated in the  $x$ -direction, and its motion was controlled by

a stepping motor. A slip ring was connected between the motor and the probe so that the sensor could be powered and freely rotated. In addition, to mitigate the propagation of vibrations caused by the motor drive to the acceleration sensor, two points between the motor and sensor were connected with a sponge.

## Artificial skin model

Vibration and friction were measured when the surfaces of five different artificial skin models were rubbed. The artificial skin models (Beaulax Co., Ltd., 10B, 10C, 10J, 10H, 10K, Japan) were made of urethane and were plaster casts of the cheeks of women in their 20s, 30s, 40s, 60s and 70s. They were  $5 \text{ mm}$  thick discs with diameters of  $50 \text{ mm}$  for 10B and 10C, and  $55 \text{ mm}$  for 10J, 10H and 10K.

## Friction and vibration measurement using the developed tactile sensor

Friction and vibration were measured when the artificial skin model was rubbed with the developed sensor. The

artificial skin model surface and the probe surface were wiped with alcohol before measurement. The scanning speed was set to 25.7 mm/s, which is within the range of normal touch and does not resonate with the sensor system, and measurements were made for 4 s. The probe rotation speed was 200 deg/s, and the probe rotated approximately 2.2 revolutions per 4 s of measurement. Five measurements were taken for each artificial skin model.

### **Friction measurement using the force plate and vibration measurement using the accelerometer attached to finger**

To verify the physical quantities measured by the developed sensors, the artificial skin model was measured with commercially available equipment. A force plate (TF1212, Tec Gihan Co., Ltd.) was used to measure friction. The artificial skin model was placed on the force plate, and the coefficient of friction was measured when the surface was rubbed with a finger. At the same time, a three-axis accelerometer (A3AX, Tec Gihan Co., Ltd.) was attached to the fingernail to measure the vibration. A 0.5 mm-thick silicon rubber sheet was placed on the force plate and fixed to prevent slippage between the artificial skin model and the force plate. The experimenter rubbed the surface of the skin model with the third finger in the same circular motion as the developed sensor. The measurement time was 5 s, and the vertical force was kept within the range 0.5–1.0 N. Five measurements were taken for each artificial skin model. The sampling frequency of the sensors was 1000 Hz for both the force plate and the acceleration sensor.

### **Surface roughness measurement of the artificial skin model**

The surface roughness of the artificial skin model was measured using the VisioScan VC98 (Courage & Khazaka) to investigate the relationship between vibration and surface roughness measured by the developed sensor. Five measurements were performed for each artificial skin model.

### **Sensory evaluation of the artificial skin model**

For comparison with the friction and vibration measured by the developed sensor, sensory evaluation of artificial skin models was conducted. The panel consisted of seven persons (five men and two women) in their 20s

to 50s. They sorted the five artificial skin models in order of perceived roughness by scanning them with their bare fingers. The surfaces of the artificial skin models and the fingers of the panel were wiped with alcohol before evaluation. There were no restrictions on the number of touches or the time of the task, and each panel completed the evaluation within 3 min. The average ranking assigned by the seven panellists was calculated for each skin model. These protocols were approved by the Human Study Ethics Committee of the Shiseido Global Innovation Center (Study No. C10126). A written informed consent was obtained from the individual panels.

### **Friction measurement using artificial skins and skin-care products**

Because the difference in friction between the five artificial skin models was small under a dry condition, we applied skin-care products to the artificial skin models and remeasured friction under conditions that increased the difference in friction. For this purpose, among the five artificial skin models, the one (10C) with the cheek shape of a woman in her 20s was used. Five commercially available emulsions and creams with different textures were used. The amount applied was 40  $\mu$ L, and it was spread using a spatula. Measurements were taken 6 min after the application, and each skin-care product was measured three times. The skin of the model lubricated with different emulsions and creams was measured with the developed sensor, and then, the friction was measured on a force plate when scanned by bare fingers. The measurement conditions were the same as those in the experiment in which the five different skin models were evaluated.

### **Evaluation of intra- and inter-rater reliability**

The reliability of the measurement using the developed sensor was examined. Three male participants in their 30s learned how to use the sensor and experienced the measurement several times. One of the participants was the author of the study; however, he had never used the sensor before this test. The participants evaluated on their own inner forearm and the inner forearms of the two other participants. One area was bare skin, and the other five areas were covered with five different skin-care products. Three types of commercially available lotion, one emulsion and one cream, all with different textures were used to differentiate the skin condition between the measurement sites. After washing the inner forearm with soap and water, the skin was allowed to stand for 10 min, and

20  $\mu$ L of each skin-care product was applied. Measurements were taken 6 min after application. Measurements were repeated twice. Therefore, the number of measurements for each participant was 36. These protocols were approved by the Human Study Ethics Committee of the Shiseido Global Innovation Center (Study No. C10128). A written informed consent was obtained from all the three participants of the study.

## Data analysis

### Developed tactile sensor

Vibration intensities were calculated from the acceleration measured by the developed sensor. The acceleration data in the  $x$ -direction, which is the direction of rotation, were analysed. The 3600 sample points were analysed for one rotation of the probe from 2.2 to 4 s after the start of measurement, during which the measurement was stable. The fast Fourier transform of the acceleration data was computed, and the amplitude of each frequency component  $y(\omega)$ , where  $\omega$  is the angular frequency, was converted to decibels ( $y_{dB}(\omega)$ ) using Equation (1). The reference acceleration ( $y_0$ ) was set to 1 G.

$$y_{dB} = 20 \log_{10} \frac{y}{y_0} \quad (1)$$

The average value in the frequency range of 5–1000 Hz was used as the vibration intensity, considering the bandwidth of the accelerometer and sampling frequency, that is, 2 kHz. Vibrations caused by the stepping motor drive were not removed because they were sufficiently small compared to the vibrations caused by rubbing the skin model. The normal force ( $F_z$ ) and friction force ( $F_x$ ) measured by the six-axis force sensor were low-pass filtered (cut-off frequency: 35 Hz), and the friction coefficient  $\mu$  was calculated using Equation (2). As with the vibration intensity, the average value of the friction coefficient from 2.2 to 4 s after the start of the measurement was obtained.

$$\mu = \frac{F_x}{F_z} \quad (2)$$

### Force plate

The coefficient of friction was calculated from the vertical force ( $F_{pz}$ ) and friction force ( $F_{px}$ ,  $F_{py}$ ) measured with the force plate when the skin models were stroked by a bare finger. After applying a low-pass filter with a cut-off frequency of 35 Hz, the combined force of  $F_{px}$  and

$F_{py}$  ( $F_{friction}$ ) was calculated using Equation (3) and the friction coefficient was calculated from Equation (4). The average value of the data for 2 s from 3 to 5 s after the start of the measurement was calculated.

$$F_{friction} = \sqrt{F_{px}^2 + F_{py}^2} \quad (3)$$

$$\mu_p = \frac{F_{friction}}{F_{pz}} \quad (4)$$

### Acceleration sensor

Vibration intensities were calculated from the acceleration in the  $x$ -direction measured by a three-axis accelerometer attached to the finger. The analysis interval was 2 s, from 3 to 5 s after the start of measurement. As in the analysis of the developed sensor, the acceleration data were fast Fourier transformed and the amplitude of each frequency component ( $y(\omega)$ ) was converted to decibels ( $y_{dB}(\omega)$ ) using Equation (1). The average value in the frequency range of 5–500 Hz was used as the vibration intensity, considering the bandwidth available for accelerometer measurement. Since the sampling frequency of the accelerometer attached to the finger was 1000 Hz, the maximum frequency used in the analysis was 500 Hz.

### VisioScan VC98

Among the measurement parameters of the VisioScan VC98, a roughness index (SEr) [6] was used and the average value of five measurements was obtained.

### Correlation analysis

The correlation coefficients between the features acquired by the sensors were calculated. Pearson's correlation coefficients were calculated between the vibration intensities acquired by the developed sensor, the vibration intensities acquired by the three-axis acceleration sensor attached to the finger, the SEr measured by VisioScan and the average rank of the sensory evaluation. Similarly, Pearson's correlation coefficients were obtained between the friction coefficients acquired by the developed sensor and the friction coefficients acquired by the force plate. Since these features were separately measured and did not correspond, the correlation coefficients were calculated from the mean values of the five skin models. A test of correlation coefficient was performed with  $p < 0.05$ .

## Intra- and inter-rater reliability

The intraclass correlation coefficient (ICC) [23] was calculated as an index for evaluating the reliability of the developed sensor measurements. In this study, ICC (1,1) was obtained as an index of intra-rater reliability and ICC (2,1) was used as an index of inter-rater reliability. The values were obtained for each vibration intensity and friction coefficient acquired by the developed tactile sensor. The ICC (2,1) was calculated using the average value of two repetitions as each participant in this study performed the measurement two times. SPSS Statistics (version 23, IBM Corp., Armonk, NY, USA) was used to calculate the ICC.

## RESULTS

### Performance evaluation using artificial skin models

Figure 2 shows measurement examples of two skin models (10B and 10K), showing data for one round of probing: acceleration in the x-direction,  $F_x$ ,  $F_z$  and friction coefficients.  $F_x$  and  $F_z$  are raw waveforms, and the friction coefficients are the values obtained from Equation (2) after

applying a low-pass filter. The force sensor signal included some noise when the signal line from the sensor flowed near the power supply. 10K exhibited greater acceleration amplitudes than 10B, and the friction coefficients were similar for both 10B and 10K.

Figure 3 shows the examples of vibration spectrum for two skin models (10B, 10K). In both skin models, there was a peak of vibration originating from the surface shape of the skin model at around 150 Hz, and it was attenuated towards higher frequencies. The bandwidth in which there was a difference between models was approximately between 150 and 800 Hz. Motor-driven vibration was around 110 Hz.

To validate the vibration and friction measurements of the developed sensor, we compared them with those of commercial equipment. Scatter plots of the vibration intensity of the developed sensor and those of the tri-axis accelerometer attached to a fingernail are shown in Figure 4a. Although the absolute values of the vibration intensities when rubbing individual skin models did not match, the Pearson's correlation coefficient between the two was  $r=0.99$  ( $p=0.0020$ ). Since the measurements by the developed sensor and by the accelerometer attached to the finger were separately conducted, the correlation coefficient was calculated from the mean value of each skin model ( $n=5$ ).

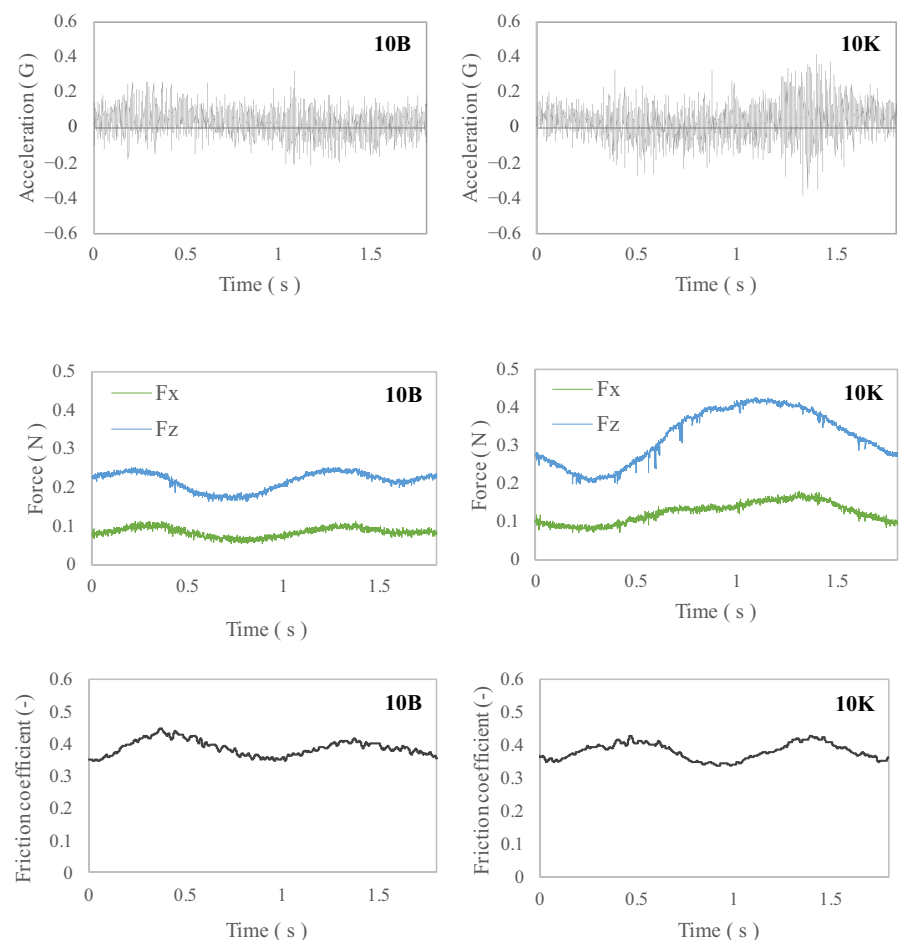


FIGURE 2 Examples of measurement results of the artificial skin models 10B and 10K with the developed sensor. From the top are the waveforms of acceleration in the x-direction,  $F_x$  and  $F_z$ , and the friction coefficient, showing data for one rotation of the probe.

Figure 4b shows a scatter plot of the friction coefficients obtained by the developed sensor and the force plate. The variation of the friction coefficient measured by the developed sensor among the five artificial skin models under the dry condition was as small as 0.1. The friction coefficients obtained with the force plate were slightly larger for 10C and 10H than those for the other three models, but the standard deviation of the measurement was large. The absolute values of the friction coefficients did not match between the two sensors. The correlation coefficient between the two sensors,  $r=0.64$  ( $p=0.24$ ), was not significant. This might

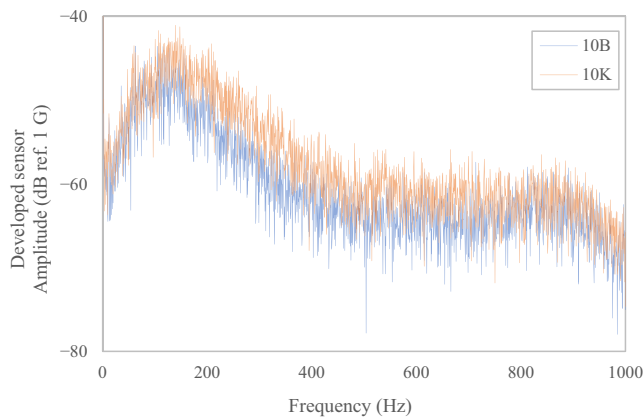


FIGURE 3 Vibration spectrum of artificial skin models 10B and 10K measured by the developed sensor.

have been due to the small difference in friction between the artificial skin models measured in this study. Therefore, in the next section, we present the results for a condition in which the friction variation between the artificial skins was increased by using skin-care lotions and emulsions.

Figure 4c shows a scatter plot of the vibration intensities acquired by the developed sensor and the surface roughness acquired by VisioScan. The correlation coefficient between the two variables is  $r=0.91$  ( $p=0.03$ ), and the standard deviation of the VisioScan roughness is rather large, which could be due to the nonuniformity of the surface roughness of the artificial skin model.

Next, Figure 4d shows a scatter plot of the mean ranks of the sensory evaluation of the surface roughness and vibration intensities acquired by the developed sensor, with a correlation coefficient between the two variables of  $r=0.99$  ( $p=0.0002$ ). The vibration intensities acquired by the developed sensor showed a linear relationship with the sensory evaluation.

## Friction measurement using artificial skins and skin-care products

As shown in Figure 4b, the variation of friction coefficients among the five artificial skin models was small. To

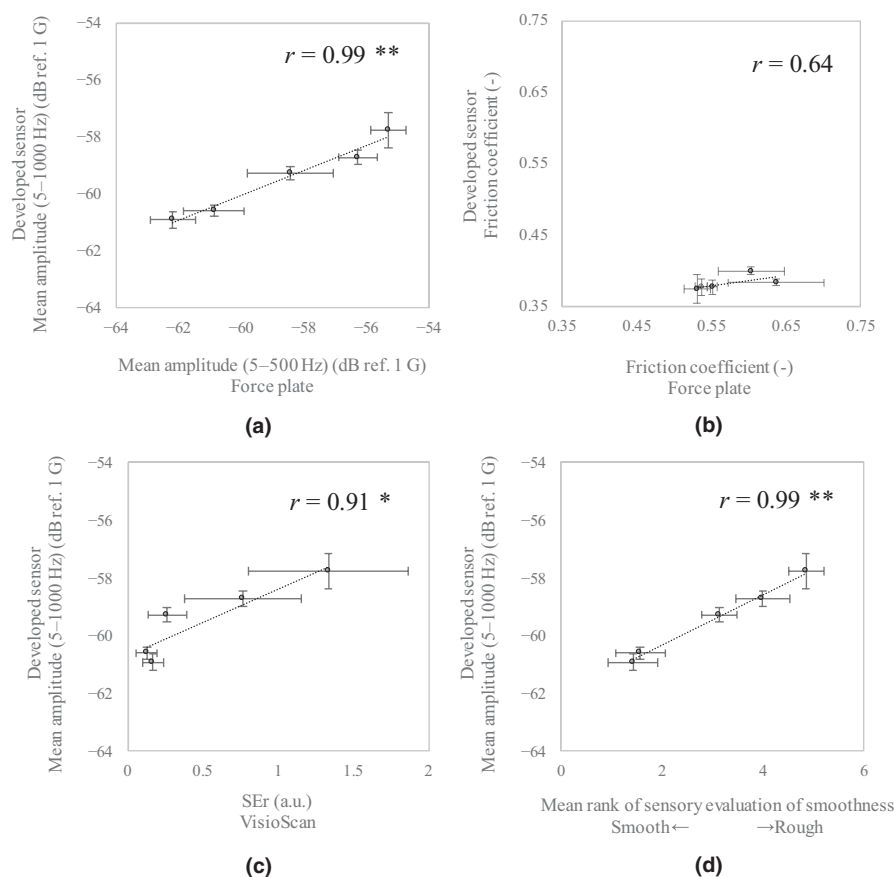


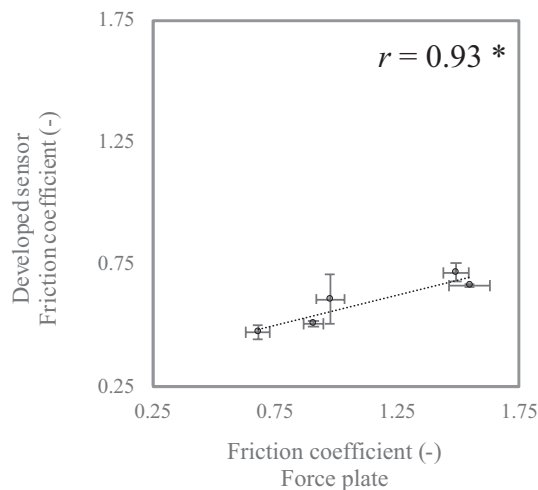
FIGURE 4 Relationship between the developed sensor, commercial equipment and sensory evaluation. (a) Relationship between the vibration characteristics acquired by the developed sensor and those acquired by the three-axial acceleration sensor attached to the finger. (b) Scatter diagram of the friction coefficient measured by the developed sensor and the friction coefficient obtained by the force plate. (c) Scatter plots of the vibration intensities acquired by the developed sensor and the surface roughness (SEr) measured by VisioScan. (d) Scatter plot of the average ranks of surface roughness in the sensory evaluation ('smooth'-'rough') and the vibration intensities acquired by the developed sensor. Error bars indicate SD,  $r$  is Pearson's correlation coefficient \* and \*\* denote  $p < 0.05$  and  $p < 0.01$  respectively.



increase the variation, we measured the friction of the skin models after applying skin-care products. Figure 5 shows the scatter plots of the friction coefficients obtained with the developed sensor and the force plate. The absolute values of the friction coefficients were different between the two measurement equipment; however, the correlation coefficient between them was  $r=0.93$  ( $p=0.02$ ). Therefore, the friction coefficients evaluated with the developed sensor exhibited a linear relationship with those evaluated by the commercial device, provided the friction coefficients of the touched object varied sufficiently.

## Evaluation of intra- and inter-rater reliability

The intra- and inter-rater reliabilities of the developed sensor were examined. The results of ICC (1,1) for each evaluator and ICC (2,1) among the three evaluators for the vibration and friction features measured by the developed sensor are listed in Table 1. The mean  $\pm$  SD, maximum



**FIGURE 5** Coefficients of friction measured by the developed sensor and force plate on the artificial skin model with skin-care products applied. Each point and the error bar represent the mean value of three measurements and the standard deviation respectively.  $r$  represents Pearson's correlation coefficient. \* denotes  $p < 0.05$ .

**TABLE 1** Intra-rater reliability ICC (1,1) and inter-rater reliability ICC (2,1).

	Vibration	Friction
ICC(1,1)		
Participant 1	0.95	0.95
Participant 2	0.98	0.99
Participant 3	0.98	0.99
ICC(2,1)	0.92	0.94

and minimum values of the vibration characteristics for the 18 conditions (3 participants  $\times$  6 skin parts/conditions) used in the evaluation were  $-68.2 \pm 2.76$  dB,  $-62.0$  dB and  $-73.5$  dB respectively. The mean  $\pm$  SD, maximum and minimum values of the coefficient of friction were  $0.66 \pm 0.22$ , 0.99 and 0.40 respectively. The variations of the vibration and friction features of the 18 conditions were sufficiently large, and ICC (1,1) and ICC (2,1) values were all greater than 0.9. The ICC criterion of 0.81 or higher is considered 'almost perfect agreement' [24], indicating that the reliability of the measurements of this sensor is sufficiently high.

## DISCUSSION

The developed sensor was designed to evaluate the tactile textures of skin-care products and bare skin. When evaluating them, humans judge skin characteristics by pushing and sliding movements [3]. Since many commercial sensors have adopted pushing motion, this study focused on sliding motion. The skin characteristics to be evaluated in the sliding motion are micro-roughness and friction. The developed sensor simultaneously measures vibration and contact force when the probe rubs the skin to evaluate these two features of skin. The sensor can be used on various body parts including cheeks and arms, and the measurement operation has been automated to improve reproducibility.

The vibration and friction measured by the developed sensor correlated with those generated by rubbing the skin with a finger, suggesting that the developed sensor is useful for evaluating the vibration and friction that humans feel when they rub their fingers on their skin. In addition, the vibration measured by the developed sensor correlated with the surface roughness of the artificial skin model evaluated by a commercially available image measuring device, suggesting the validity for skin roughness. Additionally, the developed sensor can be an alternative to commercially available friction and roughness measuring instruments. The developed sensor, the first of its kind, can fulfil these roles in a single unit.

Furthermore, the sensory evaluation for smoothness correlated well with the vibration intensities measured by the sensor, and the intra- and inter-rater reliabilities were high. Therefore, using the developed sensor instead of sensory evaluation is expected to solve the problems of the high training cost for evaluators and the low reproducibility of some sensory evaluation items among evaluators [25]. From these results, the objective of developing a sensor used for texture evaluation of skin-care products and bare skin was achieved.

In this study, only smoothness was used as a sensory evaluation attribute for the artificial skin model. However, when evaluating actual human skin, it is necessary to evaluate not only smoothness but also other attributes including softness and dryness.

In actual use, the evaluation using the developed sensor should be based on repeated measurements. This is because inconsistent measurement positions and probe contact conditions can cause measurement errors. Such replication of measurement is acceptable in cases of moisture content of the skin [26]. The time and effort required for the measurement of the developed sensor would be the same as those of conventional skin measurement devices.

One of the concepts of the developed sensor was to adopt a rubbing motion, probe shape, sliding speed and contact force close to the human exploratory motion. The shape of the probe for the developed sensor was selected based on a probe for evaluating the texture of cloth [16], but other materials and surface shapes were not considered. For example, a sensor using a probe that imitates a human finger has been developed [21, 27, 28]. For example, Kuramitsu et al. developed a probe made of urethane that imitates a human finger and employed it as a contactor for friction measurement [27]. Urethane rubber is known to wear easily and its hardness changes over time. In this study, a stainless steel probe was used in consideration of the stability of its physical properties, but the optimization of the probe material and surface shape is a subject for future study.

The probe motion speed and normal contact force of the developed sensor were determined based on the haptic exploration of a human when touching the skin. When a flexible object such as skin is rubbed at a nonconstant speed, a hysteresis originated by skin viscosity occurs [29]. This may have some influence on the evaluation of human skin. In this study, the operating speed was constant, but the human's actual explorative speed for rubbing their skin is not constant. Therefore, it is necessary to optimize the operating conditions of the probe including the speed and contact force, and the analysis method of the friction and vibration for the developed sensor in the future.

## CONCLUSION

This research developed a sensor for mechanical properties of skin, which is important for the development of skin-care products. This sensor can simultaneously measure vibration and friction with high reproducibility when actual facial skin is rubbed, which has rarely been targeted by conventional sensors. The sensor can be used in combination with conventional skin measurement devices to obtain a variety of information on the mechanical properties of the skin. Furthermore, the sensor can be used in

conjunction with sensory evaluation to investigate the relationship between textures perceived by humans and the mechanical properties of skin, which can be useful for developing skin-care products that satisfy consumers. The optimal design of skin contactor and suitable rubbing motion such as the velocity are still unclear, and their effects on measurement need to be elucidated. Furthermore, the optimization of the measurement operation and analysis remain to be studied in the future.

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## CONFLICT OF INTEREST STATEMENT

I confirm the absence of conflicts of interest in relation to this research paper.

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