Roughness evaluation by wearable tactile sensor utilizing human active sensing

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Abstract
Humans can evaluate roughness on various shaped surfaces. Conventional roughness measurement sensors are difficult to apply to curved surface or small product's surface. In this paper, a simple tactile sensor utilizing human ability based on haptic bidirectionality is developed for the roughness evaluation. Humans can move their fingers while perceiving tactile sensations and change exploratory movements like contact force, scanning velocity, direction, etc. according to haptic perception and task objective. Our developed sensor is composed of two microphones and is mounted on a human fingertip. It allows users to touch the object without haptic obstruction. Users can apply the sensor while retaining their normal haptic perception and simultaneously obtaining vibrations and sound based on the mechanical interaction between the finger and the object. First, influence of contact force and scanning velocity on the sensor output is investigated. The experimental results show that the sensor output increases with a rise in the contact force but the influence of the scanning velocity varies between individuals. Then, on the basis of the results, experiment of roughness evaluation is conducted for flat surface and curved surface. A constant normal force and scanning velocity are exerted and the collected sensor output is calibrated by using the sensor output for the middle-roughness sample. The results show that the sensor is capable of evaluating roughness on both flat surface and curved surface in the same rating.

Key words : Tactile sensor, Bidirectionality, Roughness evaluation, Curved surface, Wearable sensor

1. Introduction

Roughness evaluation has been an important inspection for the quality of product surface or precision manufacturing in the industrial field. Conventional measurement devices are probe-type sensors with a stylus, but they are hard to be applied to curved surface or small product's surface. Human fingers are still necessary for such object surface evaluation in the industrial field since human fingers are flexible and applicable to narrow space and complex shape. However, the rating by human is subjective and is difficult to record and convey. Hence, this study is aimed to develop a tactile sensor capable of evaluating roughness on curved surface and small product surface as well as flat surface to replace the inspection by humans.

Various tactile sensors and image processing technologies have been proposed for roughness or micro surface profile measurement. Image processing technologies have an advantage in wide area measurement, whereas they are not suitable for curved surface due to the limitation of height range (Li, et al., 2010). Many of tactile sensors for roughness or texture evaluation are active sensors, which include actuators for moving sensors and/or objects. For example, Sinapov et al. (2011) developed a tactile sensing system utilizing a robot arm with a three-axis accelerometer and showed that by applying several different exploratory behaviors on a test surface, the robot could recognize surfaces with different texture. In such tactile sensing system, robot arms/fingers with tactile sensors were controlled to
keep the scanning velocity and/or the contact force to be constant. In addition, object surfaces were flat. When curved surface is scanned, robot arms/fingers require to be controlled three-dimensionally in force, position, and posture. Three-dimensionally control might incur large and complicated system for the roughness evaluation. Large and complicated system is not suitable to replace the inspection that has been conducted with human's fingertip because of high cost and wide space requirements.

Alternatively, hand-held or finger-mounted tactile sensors (Kikuuwe, et al., 2004; Tanaka, et al., 2005; Ye, et al., 2007; Tanaka, et al., 2009; Peng and Rajamani, 2011) can be more easily applied to various objects since they are manipulated by a user own arm/finger. However, it is sometimes difficult to ensure sufficient stability for accurate sensing and the sensitivity decreases if they are not manipulated correctly. An extra force sensor to monitor the exerted contact force in texture measurement (Tanaka, et al., 2005), a structure and a silicone oil sheet for mechanically keeping the contact force (Tanaka, et al, 2009), and two tactile sensors with different mechanical properties in stiffness measurement (Peng and Rajamani, 2011) have been proposed to maintain the adequate sensing condition or cancel the influence of different environment on the sensing in order to ensure the sensitivity level of hand-held or finger-mounted tactile sensors. It seems that various efforts to resolve both of expanding the range of applicable objects and ensuring the sensitivity have been provided to the mechanical structure and/or signal processing of sensors. It might be difficult to assemble a simple and highly-sensitive tactile sensor in such way.

Hence, we have proposed a different approach of utilizing the humans finger as a sensor probe for the tactile sensor (Tanaka, et al., 2011). Information generated by the mechanical interaction between the human fingertip and the object surface, that is normal active touch in human haptic perception, is collected and is utilized for roughness evaluation. The sensor is very simple, and has a potential of high sensitivity by utilizing human active sensing. We took note of important characteristics of human active sensing, which are self-reference and bidirectionality. Self-reference indicates that vibrations on the skin generated by the mechanical interaction between the object and the skin cause our roughness feelings. Therefore, information based on human active sensing when the human well evaluate the roughness might be useful to roughness evaluation. In addition to the self-reference, the present study has focused on the bidirectionality for roughness evaluation on various surfaces. Exploratory movements generate the stimuli which the perception is derived from and the perception influences the movements. We can optimize or change the exploratory movements according to the perception and the task objective, consciously or unconsciously. Several psychophysical researches investigated the relationship between perception and movements for perceptual tasks in the type of motion (Lederman and Klatzky, 1998), contact force (Smith and Scott, 1996; Smith, et al., 2002), scanning velocity (Gamzu and Ahissar, 2001; Tanaka, et al., 2014), and number of the stroke (Drewing, et al., 2011). In addition to psychophysical findings, let us consider tactile displays (e.g. Okamoto, et al, 2007) and tactile enhancing devices (e.g. Kikuuwe, et al, 2005). Users can consciously or unconsciously adjust their behavior for using them (such as pressure exerted, scanning velocity and other factors) in order to optimize their perceptions according to desired tactile sensations. Tactile displays and tactile enhancing devices essentially include the haptic bidirectionality. The bidirectional relationship strongly contributes to ensuring adequate performance without imposing limiting conditions. The haptic bidirectionality might be available to apply tactile sensors to various objects. Furthermore, the bidirectionality might contribute to performing difficult evaluations such as attempting to detect very small differences and large dynamic ranges. It is expected that a tactile sensor including human active sensing characteristics could be simply applied with high sensitivity to various objects.

Ideas of using a human finger as a part of tactile sensors have been investigated for monitoring human behavior or interface devices. Mascaro and Asada (2001) proposed a nail-mounted tactile sensor capable of measuring the force applied to a finger pad by detecting changes to fingernail color. Nakatani et al. (2011) proposed a wearable contact force sensor system based on finger pad deformation due to the incompressibility of the skin. Makino et al. (2010) proposed a life log system utilizing a nail-mounted tactile sensor, in which a piezo attached to the nail detects vibrations transmitted from the finger pad, and demonstrated that touch motions used in the life could be estimated from sensor output signals. These sensors have a potential to utilize the self-reference and bidirectionality. However, they have not tried tactile evaluations of object properties. In addition, some studies measured vibrations on the skin in order to understand tactile perceptions or collect the information for rendering texture feelings. However, they were often conducted under the passive touch or required large equipments since their objectives were not the development of a sensor for tactile evaluations (Bensmaia and Hollins, 2005; Wiertlewski, et al., 2010; Martinot, et al., 2005). Vibrations measurement on the wrist by using a microphone was conducted for a basic research of human roughness.
perception (Delhaye, et al., 2012).

The purpose of this paper is to develop a simple tactile sensor using human haptic bidirectionality and self-reference that is capable of evaluating roughness on various shaped surfaces. Basis idea for the proposed sensor was presented and a prototype of the proposed sensor was assembled in a previous study (Tanaka, et al., 2011). In this paper, an easily-wearable tactile sensor is assembled and influence of contact force and scanning velocity as parameters on exploratory movements on the sensor output is investigated. On the basis of the results, roughness evaluation on flat and curved surfaces is tested. Experimental results demonstrate the availability of the developed tactile sensor.

2. Tactile Sensor
2.1 Construction of sensor and measurement system

Figure 1 shows the developed finger-mounted tactile sensor, which uses two microphones. The sensor is close to the finger pad, which will come into contact with an object, and contacts with the skin by using a spring. As compared with the previous sensor (Tanaka, et al., 2011), the spring provides the ease to wear. The sensor does not interfere with contact between the finger pad and the object. Therefore, it allows users to touch an object with bare fingers and the users can naturally perform haptic perception. Users can explore the object surface with their fingers in a natural way, perceiving roughness feeling. Hence, user's haptic bidirectionality is established in our sensor.

One of the two microphones is in contact with the user's skin, faces the skin, and performs the sensing element. Vibrations based on the normal displacement of the skin and sound caused by the mechanical interaction between the user's finger and the object surface are collected by the microphone in contact with the user's skin. We considered that vibration of the skin and sound caused by the mechanical interaction between the user's finger and the object surface might be available for roughness evaluations since the sound generated by mechanical interaction is different between the samples as well as the vibration of the fingertip surface. The other microphone is mounted on the back of the sensing element microphone, faces away from the skin, and is utilized for a noise cancellation by measuring ambient sound (noise). The microphones used (MAA-03A-L30, Star Micronics Co., Ltd.) are very small (diameter: 3 mm, thickness: 1.5 mm.,) and light (weight: 0.2 g). The distance between two microphones is 5 mm. The sensor, which is mounted on the fingertip in front of the distal interphalangeal (DIP) joint, does not distract users with annoying sensations. When the finger equipped with the sensor is moved, the contact location of the microphone does not change. The position of the sensor mounted on the finger was determined relatively according to each individual finger shape as shown in Fig. 2. Output signals from the microphones are collected using a sampling frequency of 40 kHz into a personal computer.

Fig. 1 Sensor photographs. The sensor is mounted on the fingertip in front of the distal interphalangeal joint. The sensor has two microphones. One of the microphones (microphone 1) is in contact with the user's skin and provides the sensing element while the other (microphone 2) is mounted on the back of the sensing element microphone facing away from the skin and measures ambient sound (noise).

Fig. 2 Position of the sensor mounted on finger.
2.2 Signal processing

The subtraction of the output of the microphone facing the outside from the output of the microphone facing the skin is conducted for the noise cancellation at each sampling (40 kHz) as follows:

\[ out(t) = out_1(t) - out_2(t), \]

where \( out(t) \) indicates a obtained signal at each time \( t \), and \( out_1 \) and \( out_2 \) indicate the output of the microphone facing the skin and the output of the microphone facing the outside, respectively. Gains of the two microphones were empirically adjusted for the noise cancellation before experiments. The gains were constant during all experiments. Figure 3 shows an example of sensor output \( out(t) \) obtained by a test participant sensing the roughness of a sandpaper sample. The participant scanned the sandpaper 3 times with his finger, on which the sensor was mounted. It can be observed that the amplitude of the sensor output signals is large during scanning the object.

During our experiments, power spectrum density (PSD) was calculated for evaluation using 2048 points of the obtained sensor output signals every 5.125 ms. Hanning window was applied to each segment and then fast Fourier transform (FFT) was conducted in order to obtain the PSD. Here, 90% of each segment (2048 points) was overlapped for the calculation of PSD. PSD calculation allows selecting an adequate variable according to frequency response of the sensor output for target samples. As seen in Fig. 4, it was observed that sensor outputs due to the sandpaper had relatively large response in the frequency less than about 5 kHz. The sensor output over about 5 kHz might bring low resolution to results. In addition, PSDs varied among participants and did not have a remarkable peak at a specific frequency. Detailed discussion on the PSD is described in next chapter. The resolution of a frequency in FFT was 20 Hz. Therefore, the sum of PSD from 20 to 5 kHz was calculated as a single feature presenting the intensity of the sensor output for the roughness evaluation in this paper. The sum of PSD was given using the following equation:

\[ S_{psd}(t) = \sum_{f=20}^{5000} \log_{10} \left( \frac{PSD(f)}{PSD_0(f)} \right), \]

where \( S_{psd}(t) \) indicates the sum of PSD at each time \( t \), \( PSD(f) \) indicates the calculated PSD at the frequency \( f \), \( PSD_0(f) \) performs the baseline and it is the PSD calculated by using the data collected while the finger does not touch the object. The transient response was sometimes observed in the beginning and the end of the sensing as seen in Fig. 3. However, such sensor output was not always observed. That information may be useful for tactile evaluations when the generation mechanism is clear in future.

![Fig. 3 Example of sensor output signals \( out(t) \). The sensor outputs were obtained through the subtraction of the outputs from the two microphones. A participant scanned the sandpaper 3 times with his finger, on which the sensor was mounted.](image)

2.3 Noise cancellation

Figure 4 shows the PSD of the output signals and the \( S_{psd} \) calculated from each microphone under a silent condition and that under a white noise condition in which the sound by touching sandpaper could not be heard by a participant. Figure 4 (a) shows the output from the microphone facing the skin and Fig. 4 (b) shows the output from the microphone facing the outside. Figure 4 (c) shows the output calculated by using the outputs from the two microphones according to Eq. (1). The test participant mounted the sensor on his finger and rubbed sandpaper at a constant load and a constant velocity. The white noise was inserted during the second half (after about 4.5 s). The participant rubbed the sandpaper 3
times during each half way, total 6 times.

From Fig. 4 (a), the microphone facing the skin collected the six large peaks, which was caused by rubbing the object, but the sensor output included the noise from the outside after 4.5 s. From Fig. 4 (b), the microphone facing the outside collected the signals from the outside. The sensor output $S_{ped}$ before 4.5 s is extremely small but has a similar drift output as shown in Fig. 4 (a) after 4.5 s. From Fig. 4 (c), it can be observed that the sensor output before and after white noise are almost same. An adaptive cancellation algorithm may improve the noise cancellation when the target environment is somewhat clear. In this paper, we considered to apply the sensor to various environments. Additionally, the distance between two microphones is quite smaller than the wavelength for 5 kHz sound in the air. Thus, we introduced the simple subtracting for the noise cancellation in this paper. The experimental result shows the effectiveness of the noise cancellation function.

3. Influence of Contact Force and Scanning Velocity

3.1 Samples

Sandpapers of different grades (roughness) were prepared for use in the experiments. Each sample was attached to a flat wooden plate in the size of 50 × 110 × 15 mm. Five sandpaper grades, #800, #1000, #3000, #4000, and #6000 were selected for use. Larger mesh numbers indicate smoother surfaces. Table 1 shows the average grain sizes and arithmetic average roughness $Ra$.

3.2 Procedure

Seven healthy adult persons (4 males and 3 females, age mean 22.3±0.5) participated in the experiment. All participants were strongly right-handed according to Coren's test (Coren, 1993). All participants gave their informed consent before participating in this study and they were paid for their time.

Figure 5 shows the experimental setup. The participants were instructed to use the index finger of the dominant hand (with the sensor mounted) and rub the samples by stroking towards themselves. The number of strokes was determined to be three on each trial. The participants were instructed to keep an exerted normal force and a scanning velocity to be constant at the determined values. Each sample was put on a force sensor (IFS-67M25A25-I40, Nitta Corporation) for monitoring the contact force. The participants were given feedback by seeing a monitor displaying the exerted normal force in real time during the experiment. And a stroke length and a regularly beep sound were given to the participants for adjustment of the determined scanning velocity. The stroke length was 100 mm and the participants remembered the length through a practice of stroking the finger beforehand. With the beep sound, the participants wore headphones playing white noise so that they could not hear the sound of touching the samples. During the experiment,
the participants were comfortably seated at a table. Before each condition, the participants took enough practice for keeping a contact force and a velocity to be constant at desired values by using the flat wooden plate without sandpaper, whose roughness was different from the used samples.

<table>
<thead>
<tr>
<th>Mesh number</th>
<th>Average grain size [µm]</th>
<th>Ra [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>#800</td>
<td>20</td>
<td>3.28</td>
</tr>
<tr>
<td>#1000</td>
<td>15</td>
<td>2.25</td>
</tr>
<tr>
<td>#3000</td>
<td>5</td>
<td>1.06</td>
</tr>
<tr>
<td>#4000</td>
<td>3</td>
<td>0.77</td>
</tr>
<tr>
<td>#6000</td>
<td>2</td>
<td>0.42</td>
</tr>
</tbody>
</table>

The experiment had 4 different conditions in forces, 0.3, 0.5, 0.7, and 0.9 N for a constant velocity 100 mm/s and 4 different conditions in velocities, 50, 100, 150, and 200 mm/s for a constant force 0.5 N. Each participant had all the conditions for the experiment. The order of the condition was randomized between the participants. The 5 test samples of each condition were presented once in a random order, different for each participant. The sensor output and the exerted normal force were collected during the experiment. The mean exerted normal force was 0.29±0.03, 0.46±0.04, 0.64±0.04, and 0.80±0.05 N in the 0.3, 0.5, 0.7, and 0.9 N force conditions, respectively. There were no reliable differences in the normal force among velocity conditions. The scanning velocity could not be exactly measured, but scanning time was calculated. The mean scanning time was 2.09±0.11, 1.04±0.12, 0.82±0.09, and 0.69±0.09 s in the 50, 100, 150, and 200 mm/s velocity conditions, respectively. There were no reliable differences in the velocity among normal force conditions. Thus, the force and velocity seemed to be correctly exerted in each condition.

3.3 Data processing

An example of the sensor output is shown in Fig. 6. The sensor output $S_{pad}$ has large output for each trial due to each stroke. The measured normal force was used to select sections of data corresponding to single stroke. First, the threshold used as a selection criterion was determined to be half of the normal force instructed for each condition. Then, 80% around the center of the extracted data were used for the analysis since the sensor output in the beginning and the end of each stroke sometimes had transient signals. The average $S_{pad}$ was calculated using all data of $S_{pad}$ in each extracted profile corresponding to the single stroke. Then, the average $S_{pad}$ for each trial was calculated using the averages calculated from each extracted profile.

![Fig. 6](image)

An example of measurement of normal force and PSD in a trial. The back parts in each line indicate the extracted part for the analysis. The data was collected under the normal force 0.5 N and the scanning velocity 50 mm/s.
Here, the condition of the force 0.5 N and the scanning velocity 100 mm/s was conducted twice for each participant. Therefore, the data obtained from the first-conducted session of two sessions under the force 0.5 N and the scanning velocity 100 mm/s was used for the analysis, and the data obtained from the second session was removed. In addition, the data acquisition on all samples under the conditions of 0.3 N for one of the participants and that on the samples of #1000 and #4000 under the conditions of 0.9 N for the another participant were prevented due to a malfunction in the experimental setup. The analysis was conducted without these missed data.

3.4 Results and discussion
3.4.1 Power spectrum density of sensor output

PSD of the collected sensor output was investigated. Fig. 7 shows examples of PSD for different velocities and samples for two participants. They were typical results and calculated at a certain time within the extracted data based on the processing described in 3.3. The distribution of PSD on frequency was similar within one stroke while rubbing the sample, except the beginning and end data of rubbing. Here, when the velocity is 100 mm/s, the frequencies predicted simply by \( v/L \), where \( L \) is the spatial wavelength of the surface and \( v \) is the velocity, are 5k, 6.7k, 20k, 33k, and 50k Hz for each sandpaper with 20, 15, 5, 3, and 2 µm of the average grain size, respectively. However, grains are not regularly located on the sandpaper in actuality. In addition, the sensor output might involve the frequency characteristic of the fingertip. Thus, it is hard to predict the frequency of the sensor output using \( v/L \). As seen in Fig. 7, even when a twice velocity was used like from 50 to 100 mm/s, the PSD distribution did not expand twice in frequency. Moreover, it seems that PSD distribution is not so different between the samples, but is different between individuals. This might indicate that the characteristic of the fingertip, such as stiffness, dominantly affects the sensor output. Experiments using precisely spatially-controlled surfaces and measurement of individual fingertip characteristic will be required for investigating the mechanism of the vibration and sound generation by the interaction between the fingertip and the contact object. Measurement of individual fingertip characteristic in addition to exploratory movements may lead to introduce the classification method for roughness and texture evaluations independent of exploratory movements and individuals (Fishel and Loeb, 2012). In this paper, it was sure that PSD of the sensor output tended to distribute in the frequencies less than 5 kHz for all sandpapers and all conditions and did not have a remarkable peak at a specific frequency. Thus, Eq. (2) was used for the roughness evaluation, considering to cover individual differences. The proposed signal processing might be applicable to roughness like prepared samples. Sound generation mechanism and signal processing reflecting fingertip characteristic might expand applicable texture.

![Fig. 7 Examples of PSD for various velocities and samples.](image-url)
3.4.2 Intensity of sensor output

For a comparison of the sensor outputs among different normal forces or scanning velocities, the average $S_{psd}$ for each condition and each sample and its standard deviation were calculated by using the averages from all participants. The results are shown in Fig. 8. In addition, the average $S_{psd}$ for each participant calculated for each condition by using the averages for all samples and its standard deviation are shown in Fig. 9. A slope of the linear approximation between parameters was estimated using the least-squares method for each participant and a $t$-test on the slopes from all participants as compared to zero was conducted. The result on the relation between the grain size of sample and the average $S_{psd}$ for all conditions showed a significant slope ($t_6 = 8.0, p = 0.0002$). In addition, the results on the relationship between the normal force or the scanning velocity and the average $S_{psd}$ for all samples showed a significant slope for the normal force ($t_6 = 4.1, p = 0.0063$), but no significant slope for the scanning velocity ($t_6 = 0.04, p = 0.97$). The result on the roughness follows that the sensor output decreases as surface smoothness increases. Regarding the influence of exploratory movement, there is a tendency that the sensor output slightly increases with the normal contact force for every sample, while there is not such a tendency for the scanning velocity.

These results indicate that a constant exploratory condition is required to evaluate the roughness. Smith and Scott (1996) demonstrated that participants maintained relatively constant normal force for smooth surface friction. Lederman and Taylor (1972) showed that subjective roughness estimation increases as the contact force increases, through an experiment with controlled finger force. A rise of the perceived roughness might have a strong relation with the increase of the sensor output since the sensor output involves the vibration caused by the mechanical interaction between the fingertip and the object surface. Our results are consistent with the previous findings.

Fig. 9 shows that the sensor output depends on individuals. The difference in intensity of the sensor output indicates that the roughness evaluation using the sensor requires a calibration. In addition to the intensity, the variation of sensor output differs between individuals. In particular, the influence by the scanning velocity is much different among participants. It was observed that the sensor output from three participants decreased largely after 100 mm/s or 150 mm/s and the sensor output from the other participants had a tendency of slightly increasing with the velocity. These results indicate a possibility that too large scanning velocity decreases the sensor output. Regarding normal force, it might be difficult to maintain a large constant normal force, especially for an uneven surface. Here, Tanaka et al. (2014) conducted roughness perceptual task using similar samples and normal force and scanning velocity exerted in the spontaneous exploratory movement can be observed to be around 0.5 N and around 100 mm/s. Similar values can be also observed in other related psychophysical experiments (Smith, et al., 2002). From these results and previous findings, 100 mm/s of the scanning velocity and 0.5 N of the normal force were used for the following experiment for roughness evaluation of flat and curved surfaces. 

![Fig. 8](image1.png)  
Fig. 8 Result for different normal contact forces (top) and scanning velocities (bottom) for each sample.

![Fig. 9](image2.png)  
Fig. 9 Result for different normal contact forces (left) and scanning velocities (right) for each participant.
4. Roughness Evaluation

The roughness evaluation using the developed sensor was tested for the flat surface and curved surface. From the results and discussion above-mentioned, the exploratory movement in normal force and scanning velocity was maintained at 0.5 N and 100 mm/s during the experiment. In addition, the calibration of the collected sensor output was conducted by using the sensor output from the middle-roughness sample.

4.1 Samples

Figure 10 shows the experimental setup. The flat surface used in the previous chapter and curved surface as shown in Fig. 10 were used as the samples in this experiment. The same five sandpapers as the flat surface were used for the curved surface. The samples were attached to a wooden half cylinder, which has a curvature radius 35 mm and a width 50 mm.

![Experimental setup](image)

Fig. 10 Experimental setup. Normal contact force exerted to the reference sample was measured by the force sensor and was displayed on the monitor in real-time. The participants had to touch the reference sample before touching each test sample and remember the touch.

4.2 Procedure

Eight healthy adult persons (4 males and 4 females, age mean 23.4±1.3) participated. They were strongly right-handed according to Coren's test (Coren, 1993). All participants gave their informed consent before participating in this study and they were paid for their time. The participants were instructed to rub the samples with the index finger of the dominant hand (with the sensor mounted) in the same way as the experiment presented in the chapter 3. The number of strokes was determined to be three on each trial. The participants were instructed to keep an exerted normal force and a scanning velocity to be constant at the determined values.

Each test sample was put in front of the participants and a reference sample, which was the flat wooden plate without a sandpaper, was put by the test sample, as shown in Fig. 10. The reference sample was put on the force sensor (IFS-67M25A25-140, Nitta Corporation) for monitoring the contact force. The stroke length was 60 mm. Each trial, the participants had to touch the reference sample before touching each test sample and remember the exploratory movement, in particular, the exerted force and scanning velocity. The participants could see and adjust the exerted normal force by the monitor for the reference sample. Then, the participants had to touch each test sample on the flat surface or the curved surface. When touching each test sample, the participants had to perform the remembered touching. The same regularly beep sound was given to the participants during the experiment. With the beep sound, the participants wore headphones playing white noise so that they could not hear the sound of touching the samples. The participants were comfortably seated at a table during the experiment. The determined force was 0.5 N and scanning velocity 100 mm/s.

The experiment had two sessions: one using the samples on the flat surface and the other using the samples on the curved surface. The order of the two sessions was randomized between participants. The 5 test samples of each session were presented once in a random order, different for each participant. The sensor output for the test samples was collected.
4.3 Data processing

In this experiment, the normal contact force applied for the test sample was not collected. The $S_{psd}(t)$ was used to select sections of data corresponding to single strokes. Figure 11 shows the processing of the extraction of the sensor output for the evaluation. Here, there was sometimes transient noise in $S_{psd}(t)$. Then, $S_{psd}(t)$ was smoothed by using a low-pass filter with a cut-off frequency of 2 Hz and the filtered $S_{psd}(t)$ was used as a selection criterion. The threshold of the low-pass filtered $S_{psd}(t)$ was empirically determined to be 70 above the sensor noise, in order to be available for all participants and all samples used. In addition, transient signals were observed at the beginning and end time of rubbing the sample. Thus, considering the extraction based on the smoothed output and transient signals of the beginning and end time, 60% of raw $S_{psd}(t)$ around the center of the extracted data over the threshold was used for the evaluation, in order to extracted purely sensor output while rubbing a sample. The average $S_{psd}$ for each trial was calculated using all data of $S_{psd}$ in each extracted profile. Then, each sensor output was calibrated by dividing it by the average sensor output for the middle-roughness sample #3000 on each surface.

4.4 Results and discussion

The sensor output for each sample had similar amplitude between the flat and the curved surfaces for each participant. Average of the calibrated sensor output $S'_{psd}$ for each sample and each surface and its standard deviation were calculated from the averages for all participants. In addition, the linear approximation between log-transformed average grain size of test samples and average $S'_{psd}$ for the flat surface or the curved surface was estimated using the least-squares method and a correlation coefficient between them was calculated. The result is shown in Fig. 12. The linear approximation for the flat surface was $S'_{psd} = 0.450 R + 0.712 \ (r = 0.990)$ and that for the curved surface was $S'_{psd} = 0.445 R + 0.738 \ (r = 0.951)$, where $S'_{psd}$ indicates the estimated sensor output and $R$ the log-transformed average grain size. The correlation coefficients were high on both surfaces. Furthermore, $t$-tests on the slopes between the roughness and the sensor output for all participants showed significant relationships for both the plane surface ($t_f = 5.9, \ p = 0.0006$) and the curved surface ($t_f = 4.9, \ p = 0.0017$). The results show that the sensor output decreases as surface smoothness increases on both the flat surface and the curved surface. In particular, the linear approximation was almost equal for both the flat surface and the curved surface. This result indicates that humans can well explore their fingers according to the surface and our sensor can evaluate roughness on both the curved surface and the flat surface in the same rating.

The error of the sensor output is not small as seen in Fig. 12. This is caused by the dependence on user's operation. However, by using individual operation skill, the sensor is capable of evaluating the roughness on the curved surface, where conventional measurement devices are difficult or time-consuming to evaluate roughness. Well-trained workers may lead more precisely evaluations to the sensor. The sensor has the advantage of the simple and compact system, rapid measurement, and applicability to various shapes.
5. Conclusions

This paper has presented the development of a tactile sensor utilizing human haptic bidirectionality and self-reference. The sensor is mounted on a human finger and users can apply the sensor while receiving normal tactile sensations without haptic obstruction. The sensor is very simple and is composed of two microphones, from which vibrations and sound based on the mechanical interaction between the user's fingertip and object surface are collected. Experimental results on exploratory movements showed that the sensor output depends on the contact normal force and scanning velocity. In addition, the sensor output differs between individuals. On the basis of the results, the signal processing and the procedure for the roughness evaluation were determined. The sum of PSD from 20 to 5 kHz was extracted from the collected sensor output and was calibrated for each user by using the sensor output for the middle-roughness sample. Roughness evaluation was conducted under the constant normal force and velocity. Experiment of roughness evaluation on the flat surface and curved surface showed that the sensor is capable of evaluating roughness on curved as well as flat surfaces. The linear approximation between the sensor output and grain size was almost equal for both the flat surface and the curved surface.

In our future work, we will investigate human exploratory movements based on the haptic bidirectionality and fingertip characteristic. Tanaka et al. (2014) demonstrated that humans use a greater variation in contact force for the smooth stimuli than for the rough stimuli. Introducing the adequate exploratory movement into the sensor on the basis of findings on human haptic bidirectionality and fingertip characteristic might enhance the evaluation capability of the sensor.

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