Remote Friction Reduction on Polystyrene Foam Surface by Focused Airborne Ultrasound

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***Abstract*—In recent years, various tactile displays having the ability to change their surface friction have been proposed. These displays can express many types of textures and shapes that the materials used for them do not possess. In our study, we found that the ultrasound converged on the surface of polystyrene foam reduces the surface friction. This method has potential applications in disposable and three-dimensional tactile displays. In this study, physical and psychophysical experiments were conducted to verify the effectiveness of the proposed method and to examine the basic conditions under which it is perceived. As a result, we confirmed that the surface friction was reduced on the polystyrene foam, which may be due to the squeeze film effect caused by the external ultrasound excitation of the surface.**

***Index Terms*—Surface haptics, friction, polystyrene foam, airborne ultrasound.**

I. Introduction

VARIOUS tactile displays that have been recently introduced successfully change surface friction and reproduce many types of textures and shapes. It is known that these tactile displays can express various textures and tactile sensations that the original materials used for them do not possess [1]. In addition, some studies have reported that the operability of touchscreens can be improved by providing tactile feedback to the finger [2], [3].

A "friction-change" type tactile display is mainly categorized into two types: One type uses electrostatic forces to increase the adhesion to the surface, which is perceived as a higher friction surface [4], and the other type uses a squeeze film effect from the ultrasound to reduce surface friction [5]. Based on the finger positions, these studies display several types of textures by controlling the friction. In addition, it is known that such changes in the tangential force can be perceived as changes in the surface irregularities [6]. Thus, frictional tactile displays can be applied to various domains.

We discovered a new physical phenomenon that can be used for such a friction-change type tactile display. This phenomenon occurs when the surface of the polystyrene foam oscillates from the outside when using airborne ultrasound phased arrays (AUPAs). The superficial friction is reduced when touched with a finger, as shown in Fig. 1. Based on this finding, we developed a demonstration system called "ReFriction," which remotely reduces the surface friction. The developed system was presented in a demonstration session at an academic conference [7] and many people have experienced a reduction in friction.

Although remote friction reduction can only be achieved on polystyrene foam surfaces, it has the following potential applications. First, the surfaces are disposable. Because an ultrasound device does not need to be mounted on the surface, the surface itself can be easily replaced; in addition, if the surface becomes dirty, it can be discarded. This may be useful in hygienic environments, such as hospitals. For example, if we install a replaceable polystyrene foam tactile display in a hospital registration terminal, the patients will be able to feel a tactile feedback without fear of infection.

As a second potential application, it can be used on free-form surfaces. In principle, the proposed method does not depend on the shape if the surface is made of polystyrene foam. Therefore, the friction can be changed on the surface of three-dimensional shapes. The basic extension of the object into three dimensions was investigated by Ohmori *et al.* [8]. In [8], they showed that friction reduction on polystyrene foam occurred on inclined surfaces and surfaces with continuously changing slopes by quantitatively measuring the friction change using force sensing.

A third possible application is the possibility of presenting different tactile sensations to multiple people on the same surface at the same time. As will be shown later, a surface excited by ultrasound vibrates only within a localized area of a few centimeters. Therefore, if the fingertip positions of multiple users can be detected, it is possible to present different friction patterns for each user.

So far, [7] have achieved friction reduction on polystyrene foam using ultrasound, and [8] have extended this technique and shown that it can also be applied to three-dimensional shapes. However, physical measurements such as surface amplitude

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This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Ethics Committee of The University of Tokyo under Application No. 20-341.

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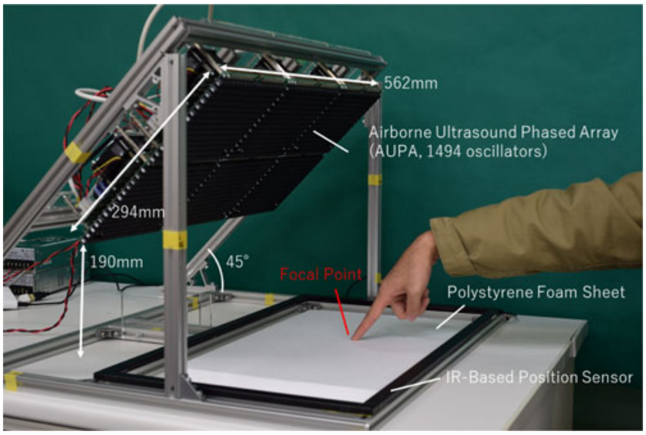

Fig. 1. Proposed system. A focal point of ultrasound is generated at the detected fingertip position on the polystyrene foam surface, and users can feel friction reduction.

have not been performed, and the conditions under which a friction reduction occurs have yet to be clarified. In particular, this phenomenon was characterized by the fact that, among the several materials tested, the friction reduction can only be felt on a surface made of polystyrene foam. The purpose of this study is to clarify the difference between polystyrene foam and other materials used in remote friction reduction, the conditions under which the friction reduction phenomenon occurs, and how much friction can be reduced through physical and psychophysical experiments.

This research focuses on a friction reduction on an externally oscillated two-dimensional surface made of polystyrene foam. We measured the displacement of the surface and determined the amount of change in the friction and how people perceive such change. However, we do not discuss herein the mode of vibration of the surface during excitation. The contributions of this study are as follows.

1) We demonstrate that polystyrene foam is sufficiently soft for external oscillations using ultrasound but sufficiently hard to avoid a significant deformation when stroked.
2) We quantitatively evaluated the extent of the friction reduction through physical measurements of the force and showed that the change in friction was sufficient to be perceived through psychophysical experiments.

These investigations are essential to understanding the basic characteristics of the proposed method and for considering future methods that can externally oscillate the surface and reduce the amount of friction.

II. Related Works

A. Friction Changing Tactile Displays

As briefly noted above, two approaches have been proposed to artificially change the amount of superficial friction. First, the frictional force is increased compared to the natural condition using an electrostatic adhesive force [9], [10].

Second, friction is reduced using the squeeze film effect caused by ultrasound; this topic has been investigated in various studies [2], [3], [5], [11], [12] and analytical models have been proposed by several recent studies [13]–[15]. As a typical application, for example, the frictional force is changed on disk-type devices in a T-Pad [16]. Takasaki *et al.* also reduced the stickiness of adhesive tape by applying ultrasound [17]. According to recent studies [18]–[20], this friction reduction is thought to be due to the combination of the squeeze film effect and the intermittent contact between a finger and a vibrating plate. However, in the following, the friction reduction on the vibrating surface is simply referred to as the squeeze film effect because such effects are not completely separated from each other.

Other studies have used a mechanical device that mimics the changes in the tangential force by pulling the strings attached to a pad below the finger [6].

In these studies, an electrical circuit or mechanical actuator was attached to the device. However, our method does not require any equipment on the surface; instead, it is installed in the environment. Therefore, the surface can be disposable and three-dimensional.

B. Airborne Ultrasound Tactile Displays

In 2008, Iwamoto *et al.* proposed an airborne ultrasound tactile display providing tactile sensations in midair [21]. In 2013, Carter *et al.* also reported a similar configuration to achieve mid-air tactile feedback [22]. Some studies have combined a tactile sense with aerial volumetric images [23], [24]. Such devices have recently been used to reveal the basic haptic characteristics of human users [25]–[27].

These studies focused on the realization of midair haptic feedback. However, our method does not directly stimulate human fingers, but it oscillates the target surface and changes its perceived texture.

III. Proposed System

In this study, we propose a method that remotely reduces the surface friction using AUPAs. Fig. 1 shows the setup of the proposed method. In our pilot study, we found that the most effective friction reduction was observed on polystyrene foam with a density of 17.6 $\mathrm{kg/m^3}$, in which polystyrene foam was used as the target surface. We also found that the AUPAs should be set at an angle of approximately $45^\circ \pm 20^\circ$ to the surface. Therefore, six units of AUPAs, with a total of 1494 transducers, were set at an angle of 45°, as shown in the figure. The target surface is replaceable, and the finger contact position is detected using an infrared(IR)-based position sensor (TYCO TOUCH, PPMT-IR-027ZV-NG). When a user moves their finger on the surface, the system detects the position of the finger and focuses the ultrasound at the detected position.

In this system, the two-dimensional coordinate fingertip position, acquired by the IR sensor, is sent to a computer, and the focus position in the three-dimensional coordinate system of the AUPAs is calculated in real time. The transformation matrices between the surface, IR sensor, and AUPAs were calculated based on the geometric dimensions of the metal frame.

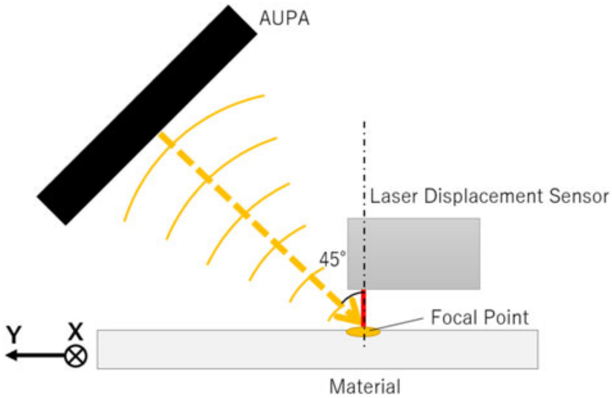

Fig. 2. Overview of surface displacement measurement.

IV. Experiments and Results

In our pilot study, the following two observations were made.

1) When a user stroked the surface of the polystyrene foam where the ultrasound was focused, the surface friction was perceived to be reduced.
2) Other materials, such as paper or acrylic, cannot be used to reduce the amount of friction.

We quantitatively evaluated the observations through the following experiments.

A. *Experiment1: Vibration on Target Surfaces*

First, we measured the displacement of the surface when the ultrasound focus was formed on several materials. Fig. 2 shows the experimental setup for the displacement measurement. A laser displacement sensor (KEYENCE, LK-H023) was placed above the surface. We created a focal point on the surface of the materials below the laser sensor. We prepared four different materials, i.e., polystyrene foam, acrylic, paper, and cardboard. We chose these four materials for the following reasons: Polystyrene foam (Yamatami, eps60-6045-20) is the most friction-reducing material used in our preliminary experiments. Acrylic (Sakura-jushi, OAP45 C) has a hard and smooth surface similar to that of glass used for general touch panels. Paper (KOKUYO, PPC-NAA4) is a material with a fine texture on its surface, similar to polystyrene foam. Cardboard (Rengo, A flute) is a material containing a layer of air inside, similar to polystyrene foam. By comparing these characteristics, we aimed to clarify the contribution of polystyrene foam. The physical properties of the four materials used in the experiments are listed in Table. I. The thicknesses of the materials were 20 mm for polystyrene foam, 5 mm for paper (with approximately 50 stacked sheets), 5 mm for acrylic, and 5 mm for cardboard. All materials were set on a hard surface.

During the experiment, we applied the maximum intensity from the six units of AUPAs, which exerted 27 mN, within an area of approximately 1 cm^2 around the focal point, provided that the target surface had sufficiently high mechanical impedance.

For the polystyrene foam surface, we also measured the distribution of surface displacement around the focal point of the ultrasound to investigate the vibrating area on the surface.

TABLE I
Physical Properties of the Materials Used in the Experiment

materials	Density [kg/m^3]	Thickness [mm]
Polystyrene foam	17.6	20
Paper	734	5
Cardboard	80	5
Acrylic	1190	5

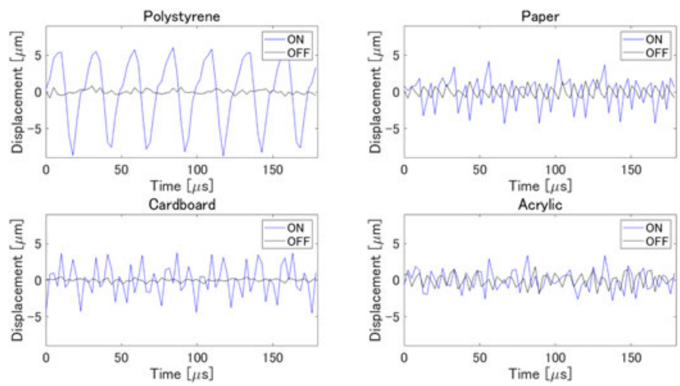

Fig. 3. Measured surface displacement in time series.

Results1

Fig. 3 shows the measured displacements of four different material surfaces in the time series. The black line shows the no-ultrasound condition (noise level). It is clear that only the surface of the polystyrene foam oscillated regularly when ultrasound was applied. The period for the change in displacement of the polystyrene foam surface was approximately 25 μs, which is consistent with the period of the driving frequency of the AUPA (40 kHz). The other surfaces also appeared to vibrate more than when the ultrasound was off; however, there was no appearance of excitation at 40 kHz, indicating that the surfaces were not properly excited with ultrasound.

Fig. 4 shows the spatial distribution of the amplitude on the surface of polystyrene foam. The vertical axis shows the 40 kHz component of amplitude obtained using FFT for the observed displacement in the time series. The directions of the $x-$ and $y-$ axes are as shown in Fig. 2, and the origin of the xy plane is set to the center of the focal point of the ultrasound. It is clear that the surface vibration was localized in an area approximately 2 cm in diameter. Because the focus of the ultrasound is approximately 1 cm in diameter, it is confirmed that only a comparable sized region oscillates. This means that the polystyrene foam was excited locally, rather than in a mode vibrating the entire plate.

B. *Experiments2: Measurement of Frictional Force*

To determine whether the friction on the polystyrene foam surface decreased with the application of ultrasound, we measured the frictional force acting between the finger and surface. The experimental setup is illustrated in Fig. 5. We used a force sensing stage (Tec Gihan, TF-2020) to measure the minute force generated when a finger touches the surface. This

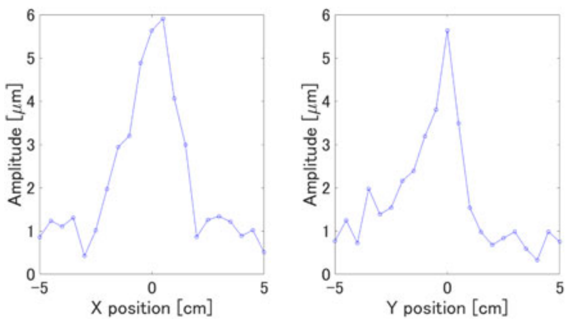

Fig. 4. Amplitude distribution on the polystyrene foam surface around the focal point.

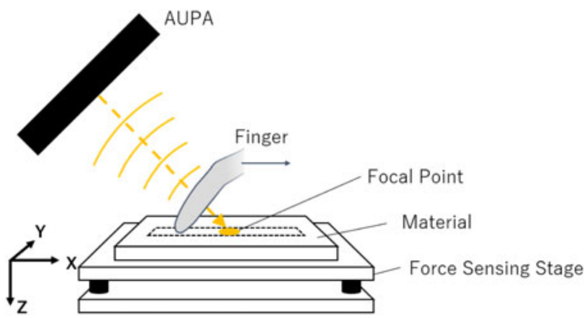

Fig. 5. Overview of frictional force measurement.

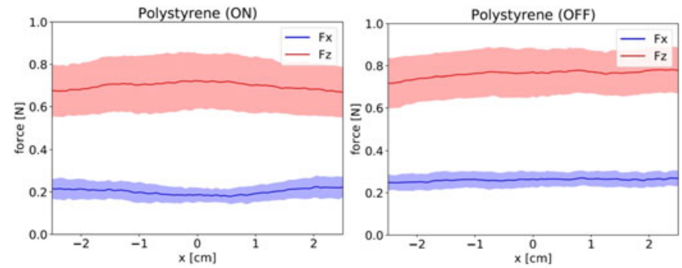

Fig. 6. Measured normal F_z and lateral F_x forces with/without ultrasound conditions for the polystyrene foam surface. Solid lines and light-colored areas represent average values and standard deviations of 20 trials, respectively.

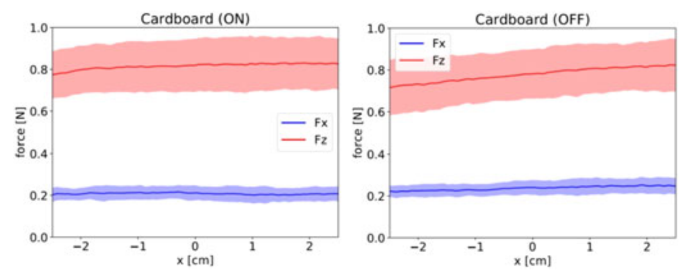

Fig. 7. Measured normal F_z and lateral F_x forces with/without ultrasound conditions for the cardboard surface. Solid lines and light-colored areas represent average values and standard deviations of 20 trials, respectively.

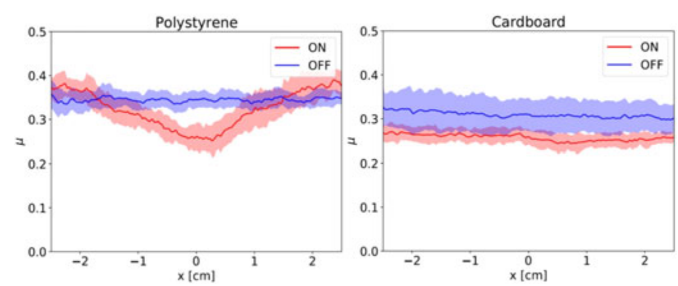

Fig. 8. Calculated friction coefficients on the surface of polystyrene foam and cardboard. Solid lines and light-colored areas represent average values and standard deviations of 20 trials, respectively.

device can measure the vertical and horizontal forces simultaneously at a sampling rate of 10 kHz.

One of the two target surfaces, polystyrene foam and cardboard, was fixed to the device. These two samples were chosen because they showed higher amplitudes than the other two materials in the previous surface displacement measurements. We measured the normal force, F_z, and frictional force, F_x, generated when one of the authors stroked a 10 cm line on the surface with the right index finger in the x-direction from negative to positive. Ultrasound was constantly applied at the center of the line, and its spatial distribution was the same as in the previous experiment, as shown in Fig. 4.

If the ultrasound reduces the friction on the polystyrene foam surface near the focal point, it is expected that the friction coefficient μ will decrease near $x = 0$. Furthermore, to confirm that the friction reduction is due to the ultrasound, we also conducted the same measurement without using ultrasound for each material. Each condition was measured 20 times and the results were averaged.

We also measured the change in frictional force when the surface amplitude was varied. Because the decrease in frictional force only occurs on the surface made of polystyrene foam, this measurement was conducted only under polystyrene foam conditions. First, the relationship between the ultrasound intensity, which can be controlled by changing the voltage given to each transducer, and the surface amplitude was measured to clarify the relationship between the surface amplitude and the friction coefficient. Then, the friction coefficient was measured under the same ultrasound intensity conditions, and the change in the friction coefficient with respect to the surface displacement was evaluated.

Results2

We show the measured normal and lateral forces on the surfaces of the polystyrene foam and cardboard in Fig. 6 and 7, respectively. Each graph shows the average of 20 trials, and the light-colored area shows the standard deviations. It can be seen that the normal and lateral forces are similar among the four experimental conditions; however, for only the condition on the polystyrene foam surface with ultrasound, the lateral force F_x diminishes near $x = 0$.

The calculated friction coefficients ($\mu = F_x/F_z$) for the two cases are shown in Fig. 8. Each graph shows the results with and without ultrasound conditions. Each line shows the average of 20 trials, and the light-colored area shows the standard deviations. The horizontal axis shows the finger position when the friction coefficient is measured, and the center of the ultrasound focus is set at $x = 0$.

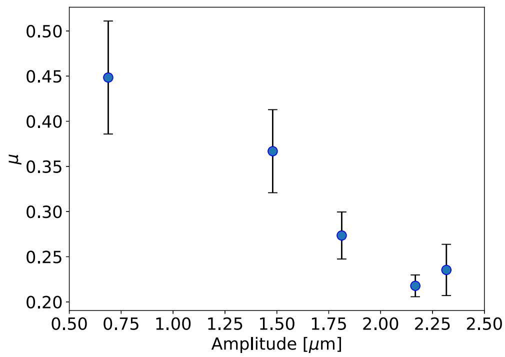

Fig. 9. Measured minimum friction coefficient when the surface amplitude is varied. The mean and standard deviation of 20 trials are shown.

It is clear that a localized decrease in the friction coefficient was observed under only the polystyrene foam condition with ultrasound when a finger passed near the focal point. The average coefficient of friction for the polystyrene foam was 0.34 and the minimum was 0.33 when the ultrasound was turned off (blue line). In other words, the friction coefficient is almost constant regardless of the position. By contrast, the average minimum value with ultrasound was 0.25 (red line near $x = 0$), which indicates that the friction coefficient decreased by 26%.

Under the cardboard condition, the average friction coefficient is lower when ultrasound is on than when it is off; however, a localized decrease in friction similar to that of polystyrene foam cannot be observed. To evaluate the locality of the stimuli, t-tests were conducted on the difference between the mean and minimum values in the on and off states for each condition. For polystyrene foam, there was a significant difference ($p < 0.001$) between the mean and minimum values for the on and off conditions. In other words, the change in the spatial friction coefficient during the on-state was significantly larger than the change in the measurement error during the off state. However, no significant difference ($p = 0.95$) was observed for the cardboard. This result indicates that the amount of friction is reduced near the focal point on the polystyrene foam surface. However, in the case of cardboard, the difference in spatial frictional change with and without ultrasound was small.

The variation of the friction coefficient with respect to the surface vibration amplitude is shown in Fig. 9. The horizontal axis shows the surface vibration amplitude at 40 kHz in micrometers, and the vertical axis shows the average of 20 trials, at which the friction coefficient was the lowest when one of the authors stroked the surface. Error bars indicate the standard deviation. From the figure, it was confirmed that the friction coefficient is negatively proportional to the surface amplitude, which is consistent with the results of conventional studies into change in ultrasound-based friction.

This result is qualitatively consistent with the results shown in Fig. 8. When the focal point was irradiated at a single point, a bell-shaped distribution of the vibration amplitude was created (Fig. 4), and the actual frictional force changed smoothly with a distribution with corresponding size to that for the vibration amplitude (Fig. 8).

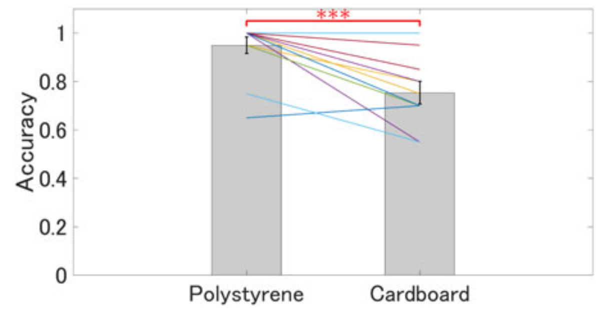

Fig. 10. Correct answer rate of the psychophysical experiment for the polystyrene foam and cardboard surfaces. The results are significantly different ($p = 0.0003$). Each color line corresponds to the results of one subject.

C. Experiment3: Psychophysical Experiment

We attempted to confirm whether the external ultrasound changed the subjective feeling of friction only when the target surface was made of polystyrene foam. The experiment was designed as follows: The subjects sat on a chair and placed the index finger of their right hand on the target surface. One of the two target surfaces, polystyrene foam and cardboard, was randomly selected as the first surface. Two areas on the selected target surface were set as the location of the stimulation. The areas were circles both with a diameter of 5 cm, 10 cm apart from each other. One of the two areas was randomly activated by ultrasound using AUPAs. After stroking the two candidate locations, the subjects were asked to identify the region with the lower amount of friction. Twenty trials were conducted on one subject per surface. The location of the stimulus (left or right) was randomized, and the number of times the stimulus was applied for each side was designed to be even. After 20 trials, the first surface was replaced with the other.

Because the ultrasound stimulation causes audible noise and airflow, we eliminated them using noise-canceling headphones playing white noise, and a fan was used to intentionally and continuously produce wind during the experiment to mask the original airflow by the ultrasound.

Fourteen subjects (10 men and 4 women) participated in the experiment. The experiment was approved by the Ethics Committee of The University of Tokyo (Application No. 20-341).

Results3

Fig. 10 shows the results of the psychophysical experiments. The vertical axis indicates the correct answer rate, which demonstrates how often each subject answered that the area activated with ultrasound had less friction. Each line shows how the responses of the subjects corresponded to each other under the two experimental conditions. A total of 10 of the 14 subjects scored 100% when the surface was made of polystyrene foam. One subject could not feel anything while another subject answered completely correctly under both conditions, and the others answered more accurately with polystyrene foam than with cardboard. After the experiment, almost all of the subjects stated that the difference was much clearer with polystyrene foam than with cardboard.

The average correct answer rate was 95% for the polystyrene foam condition. By contrast, the correct rate was 75% for the cardboard surface. Based on the paired t-test, these two results were significantly different ($p = 0.0003$).

Two possible factors made the subjects feel friction reduction above the chance level when cardboard was applied: "surface vibration" and "heat generated by ultrasound," which are discussed in the next section.

V. Discussion and Limitations

A. Possibility of Squeeze Film Effect

Because the largest amplitude of vibration among the four materials was observed on the polystyrene foam surface when the ultrasound was irradiated, it is probable that effects similar to the general squeeze film effect occurred on the polystyrene foam surface.

In a previous study [5], it was confirmed that the friction diminishes owing to the squeeze film effect if the amplitude of the surface displacement is more than 1.5 μm. For the polystyrene foam surface, the observed displacement was more than 5μm; thus, it is natural to consider that the change in perception is due to the squeeze film effect. As mentioned above, it should be noted that this friction reduction is caused by a combination of the squeeze film effect and the intermittent contact between the finger and surface. In particular, previous studies [18], [19] reported that intermittent contact is formed with an amplitude of more than approximately 1 μm. Because the amplitude of the polystyrene foam surface is much larger than the value, intermittent contact was considered to be sufficiently formed on the surface.

Note that the measurement of the surface displacement was made without a finger; therefore, the actual displacement at the finger was not known when the finger was placed on the surface, which is discussed further in the next section. However, in present results, there was a correlation between the vibration amplitude under the no-finger condition and the perceived tendency of the subject during the experiment. Therefore, when a finger is placed on a surface, there might be differences in vibratory amplitude among the materials, similar to those under the no-finger condition, causing differences in the friction perceived.

B. Difficulty in Measurement of Displacement When Touched

When a finger is placed on the polystyrene foam surface, the vibration amplitude is expected to be significantly attenuated compared to when it is not placed there. It would be desirable to be able to measure the amplitude of the vibration under this situation; however, it is difficult to do this using the current setup. For example, a method for estimating the amplitude of the vibration by placing a sensor on a vibrating glass was shown in an existing experiment on the change in friction by ultrasonic waves [28]. However, it was found that the entire polystyrene foam plate was not excited in a certain resonant mode, but rather in a narrow area of approximately 2 cm in diameter near the focal point of oscillation. When a finger touches the surface, it is difficult to measure the vibrations directly underneath, and measurements must be made within the vicinity of the finger. Owing to the arrangement of the ultrasonic transducer and the finger, it is difficult to do this without interfering with the propagation of the ultrasound.

C. Material Limitation

As shown in the experimental results, a clear change in friction was observed only on the polystyrene foam surface. The large vibration displacement observed in polystyrene foam is considered to be due to its low characteristic acoustic impedance of the material, which is calculated by multiplying the density ρ by the speed of sound c. The density of the polystyrene foam used in this study was measured to be 17.6 $\mathrm{kg/m^3}$. For general solid materials, the density is more than 1000, e.g., 1190 $\mathrm{kg/m^3}$ for acrylic. Thus, the order of the characteristic acoustic impedance for general solid materials is more than 10^6, while it can reach 10^4 for polystyrene foam if the speed of sound is assumed to be similar to that of a general solid object. Because the characteristic acoustic impedance of air is approximately 410, it can be considered that polystyrene foam, which has a value relatively close to air, absorbs more energy than the other materials and the surface is then sufficiently excited.

Because the cardboard used for this comparison has a structure with a layer of air in it, we should not consider its properties for ultrasound in terms of its characteristic acoustic impedance of the material, but rather discuss it in terms of the mechanical impedance determined by the structure. In this study, a superficial deformation also occurred on the cardboard and was perceived at above the level of chance. This result indicates that if the mechanical impedance is designed with a suitable structure, it will be possible to produce a remote friction reduction effect independent of specific materials such as polystyrene foam. A recent paper showed that a thin film membrane with a resonant frequency of 40 kHz could reduce its superficial friction when ultrasound was applied from outside [29]. This paper is a first step in investigating the conditions for using polystyrene foam as a material to produce a remote friction-reduction effect.

Furthermore, it should be noted that this paper focused only on the frequency of 40 kHz. When using different frequencies, the resulting friction reduction properties may differ from this paper. However, at present, it is difficult to realize the system operating at other than 40 kHz due to the hardware limitation of AUPA. Tactile representation and the investigation of optimal materials and surface geometries at different frequencies can be topics of future work.

D. Vibratory Area on the Polystyrene Foam Surface

The area of excitation when the ultrasound was applied to the polystyrene foam surface was approximately 2 cm in diameter under the no-finger condition, which was comparable with the focal diameter of ultrasound and well localized. Therefore, it is unlikely that the vibrations under the finger are the result of excited vibrations propagating laterally across the polystyrene foam surface. We believe that a friction reduction occurs as the finger passes on a part of the focal point.

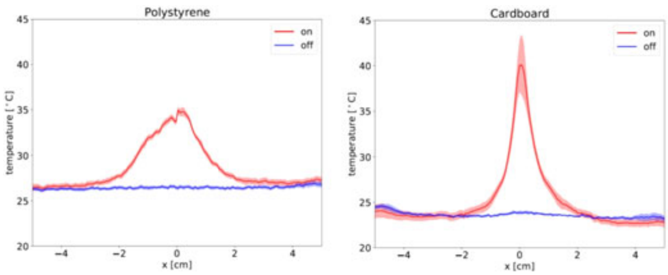

Fig. 11. Thermal distribution on the surface of polystyrene foam (left) and cardboard (right) around the focal point with/without ultrasound conditions. Solid lines and light-colored areas represent average values and standard deviations of 10 trials, respectively.

Further investigation is needed to determine which vibration modes are excited on the polystyrene foam surface.

E. Difference in the Friction Coefficient

In Fig. 8, the coefficient of friction calculated for the cardboard is always smaller under the ON condition. The force plot (Fig. 7) shows that the vertical force (red line) tends to increase under the ON condition. We considered the increase in the normal force on the surface to be due to the acoustic radiation pressure of ultrasound on the target surface under the ON condition, and measured the force. As a result, the difference in the normal force with and without ultrasound was approximately 0.02 N, which is reasonable because the presented force of the ultrasound is several gf, which is in the same order as 0.02 N. However, this value is too small to explain the difference in the experiment. Therefore, the increase in the vertical force owing to the acoustic radiation force of the ultrasound alone cannot explain this variation.

There is a possibility that the surface of the cardboard vibrates and the surface friction decreases as a result. This needs to be verified in more detail in the future. However, it is clearly shown that local frictional changes did not occur under the cardboard condition as they did in the polystyrene foam, and this difference is thought to have affected the perceptual sensitivity and cause the difference in response tendency in the psychophysical experiment.

F. Effect of Heat

When the surface of polystyrene foam is excited by ultrasound, as evidenced by the localized vibrations, the viscosity of polystyrene foam is high, and the energy of the vibrations is converted into thermal energy on the spot. Therefore, we measured the temperature change during ultrasound irradiation using a thermal camera (testo, testo 883) and considered the effect of this temperature change on the user perception.

Fig. 11 shows the temperature distribution when the surfaces of the polystyrene foam and cardboard were stroked under the same conditions as in the psychophysical experiment. One focus was created on the origin ($x = 0$) and each graph shows the average of 10 trials. The temperature of the polystyrene foam surface at room temperature was approximately 27 °C, and that of the cardboard surface was approximately 24 °C. When these surfaces were irradiated with ultrasound, it was confirmed that the area near the focal point was heated locally, as shown in the figure. The degree of temperature increase differed between the polystyrene foam and cardboard surfaces. The temperature of the polystyrene foam increased by approximately 8 °C to 35 °C, and that of the cardboard increased by approximately 16 °C to 40 °C.

Although the temperature increased as shown above, the high-temperature area was only a few centimeters, and the fingertip passed through this area in approximately 0.2 s under the experimental stroking conditions. Therefore, this local temperature rise was not perceived as a temperature change as long as the finger was moving, and there were no comments on the temperature change from the subjects in the experiment. However, we cannot deny the possibility that this temperature change affected the judgment of the psychophysical experiment. The reason why the perception of the stimulus was higher than the level of chance even for the cardboard condition, where the surface was not vibrating at the applied 40 kHz, might be because the subjects were aware of such a temperature change.

When considering that the larger temperature change was more discriminating, the percentage of correct responses should have been higher under the cardboard condition than under the polystyrene foam condition because the absolute value and the amount of change were larger for the cardboard. However, the results show that polystyrene foam was perceived better than cardboard.

If one associates the temperature change with friction, it would be natural to perceive the higher temperature as having a higher amount of friction because of the relationship with frictional heat. However, the results show the opposite: The higher temperature spot irradiated with ultrasound was perceived as having a lower amount of friction. This may be due to the fact that the effect of frictional change was greater than the unconsciously perceived change in temperature increase.

In summary, during the psychophysical experiment, there was a difference in temperature change depending on the presence or absence of ultrasound irradiation. However, from the following two factors, we believe that our experiment illustrates that the frictional change is sufficiently large to be perceived by the user: 1) The finger moves instantaneously over the warm area without the person being able to perceive it, and 2) the resulting perceptual tendency is inexplicable if the temperature change is perceived.

When a focal point is formed at a certain location and the fingertip is kept fixed there, the heat between the fingertip and the surface increases, and as a result, the temperature can increase up to approximately 45 °C, which is the temperature at which pain is felt [30]. However, such a situation in which the finger remains in one place and is continuously irradiated with ultrasound is not a common use of our system. This is because the fingertip must move to feel the change in friction. We also confirmed that the temperature rise did not reach a painful level when the fingertip was moving. To be safer, we can simply turn off the ultrasound when the fingertip is not moving.

VI. Conclusion

This study proposed a tactile display that can remotely change the friction of surfaces made of polystyrene foam using focused ultrasound.

Through the experiments, we found the following: 1) Only the surface made of polystyrene foam was sufficiently oscillated with a focused ultrasound. 2) The frictional force between the finger and the polystyrene foam surface was actually reduced when the ultrasound was applied. Finally, 3) the reduction of friction on the polystyrene foam was sufficient to be perceived by the user. These observations suggest that a squeeze film effect may occur even on surfaces oscillated externally by ultrasound, similar to common ultrasonic friction reduction devices.

We conclude that this system is capable of remotely changing the amount of friction, thereby allowing the display to be disposable or three-dimensional, which makes it suitable for some practical applications.

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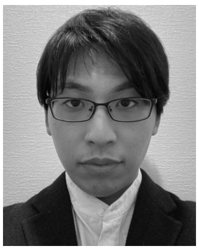

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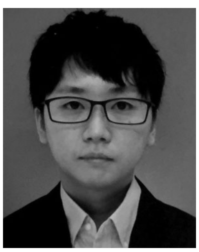

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