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Displaying Sense of Adhesion by Electro-tactile Display

Taisei Sakamoto
The University of Electro-Communications
Tokyo, Japan
sakamoto@kaji-lab.jp

Michiru Sobue
The University of Electro-Communications
Tokyo, Japan
sobue@kaji-lab.jp

Keigo Ushiyama
The University of Electro-Communications
Tokyo, Japan
ushiyama@kaji-lab.jp

Izumi Mizoguchi
The University of Electro-Communications
Tokyo, Japan
mizoguchi@kaji-lab.jp

Hiroyuki Kajimoto
The University of Electro-Communications
Tokyo, Japan
kajimoto@kaji-lab.jp

***Abstract*—We experience a sense of adhesion when touching a lotion or adhesive tape with a finger and attempting to pull it off. This sense of adhesion is considered an important element of tactile sensation. However, previous methods for presenting this sensation have been limited, and most require relatively large devices. This study proposes a compact method for presenting a sense of adhesion using an electro-tactile display. The electro-tactile display can be made wearable, and it allows flexible control over stimulation timing and area. We propose a method for evoking a sense of adhesion by delivering cutaneous electrical stimulation at the timing when a pulling force is generated between the finger and the adhesive object. Additionally, we investigated a method for reproducing changes in the contact area. Experimental results showed that electrical stimulation successfully induced a sense of adhesion when the finger was lifted from the adhesive surface. The results also suggest that stimulation timing contributes more to the perception of adhesion than changes in the stimulation area.**

Keywords—area, electro-tactile display, sense of adhesion, timing, wearable

I. Introduction

Advances in virtual reality (VR)-related technologies, such as improvements in computer performance and graphics, and device miniaturization, have led to the widespread use of VR-based content. In VR environments, the presentation of haptic sensations upon contact with an object is believed to create the illusion that the object does exist, and help enhance the immersive experience. Many methods for presenting haptics-related sensations such as texture, warmth and softness have been proposed [1][2][3].

One of the realistic tactile sensations when touching an object is the sense of adhesion. In this study, the sense of adhesion is defined as the sensation of the skin being pulled when a finger comes into contact with an adhesive surface and is pulled away from the surface, as experienced with lotion, adhesive tape, or sweaty human skin. In the research field of haptics, the sense of adhesion is often treated as part of frictional sensation, as it occurs when a finger slides on an adhesive surface [4][5], and research on the sense of adhesion that occurs when a finger is pulled away from an adhesive surface, as considered in this study, remains relatively limited. However, presenting the sense of adhesion is expected to enhance realistic haptic experience in VR spaces, similar to texture, warmth, and softness.

The sense of adhesion can be divided into force sensation and cutaneous sensations. The force sensation component can be relatively easily presented using a force display such as TouchX, as the force should be applied to resist finger movement away from the contact surface. On the other hand, the sense of adhesion associated with the texture of lotion and human skin, as described above, is considered a more subtle sensation, primarily influenced by cutaneous sensation. Regarding the sense of adhesion in the cutaneous domain, it is known that changes in contact area exhibit significant hysteresis during the process of pressing down and pulling up the finger [6]. Building on this understanding, a method for presenting a sense of adhesion using air suction has been proposed [6]. Another example using a tape with adhesive strength that varies with temperature has also been proposed [7].

On the other hand, conventional methods of presenting the sense of adhesion, whether relying on force sensation or cutaneous sensation, require large-scale devices to be installed in the environment. From a portability and cost perspective, a method capable of presenting the sense of adhesion in a wearable format is desired.

In this study, we propose a method for presenting a sense of adhesion by combining cutaneous sensation via an electro-tactile display with simple force sensation using a finger cap fixed to a desk. Various methods for presenting tactile sensations have been proposed, including mechanical vibration [8], focused ultrasound [9], and electrovibration [10]. Among these, the electro-tactile display is low-cost, easy to miniaturize, and relatively easy to use as a wearable tactile presentation method [11][12][13]. In addition, by controlling the polarity of the electrodes, two types of stimulation can be presented: anodic and cathodic stimulation, which roughly correspond to vibration and pressure sensations, respectively [14]. As a previous study [6] suggested a relationship between the sense of adhesion and changes in contact area, reproducing the spatial distribution of stimulation would be desirable, making electro-tactile displays a suitable choice, as they allow individual electrode control and can achieve high spatial resolution with relative ease. In fact, it has been confirmed that a sense of softness can be presented by changing the stimulation area in response to finger pressure using electro-tactile displays [3].

The aim of this study is to present a sense of adhesion by combining cutaneous sensation via an electro-tactile display with simple force sensation by securing a finger cap to a desk. The sense of adhesion is presented using an electro-tactile display to simulate the pulling force when the finger is lifted and the gradual change in contact area observed in a previous study [6], and its effectiveness is evaluated.

II. Device

The device used in this study is shown in Fig. 1. This device provides electrical stimulation through electrodes made of a flexible substrate, which are placed inside a 3D-printed ABS finger cap (Stratasys F120). A 6-axis force sensor (Touchence, S18C1-WM155-K1-P4I) is positioned directly under the finger cap. The finger cap and force sensor are fixed with double-sided tape. When the finger exerts a pressing or pulling force, this force is detected by the force sensor, and an electrical stimulation is applied accordingly.

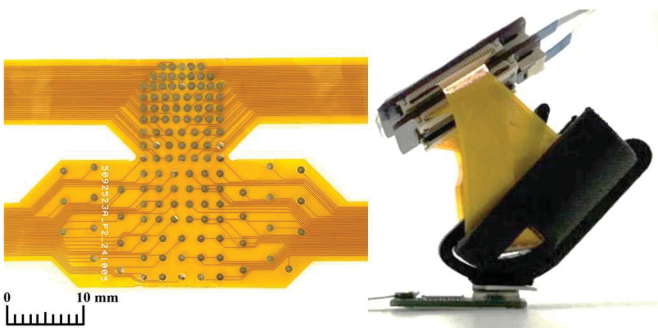

Fig. 1. (Left) Electrode, (Right) External view of the fingertip section of the experimental apparatus. The electrode is housed inside the finger cap, and the force sensor is positioned directly beneath the finger cap.

A diagram of the electro-tactile display is illustrated in Fig. 2. The electro-tactile display consists of a main board that includes a microcontroller (Seeed Studio, ESP32S3) connected to a PC to control the electrical stimulation, a D/A converter (Analog Devices, AD5452), an A/D converter (Analog Devices, AD7476), and a current control circuit. It also includes a switching board with a set of high-voltage switches (SuperTex, HV513) and a flexible circuit board with 128 electrodes. The dimensions of the electrodes were determined based on the tactile resolution distribution of the index finger measured by Sobue et al. [15]. For example, the distance between the centers of the electrodes is 1.25 mm at the fingertip, 2.0 mm near the middle of the finger pad, and 2.5 mm near the first joint of the fingertip. The electrodes are arranged from the joint to the fingertip, allowing tactile sensations to be delivered to the entire fingertip. The flexible circuit board is attached to the inner surface of the finger cap, allowing electrical stimulation to provide tactile sensations to the entire fingertip. The finger cap is designed to fit the index finger, so the finger is in constant contact with the electrode throughout the experiment.

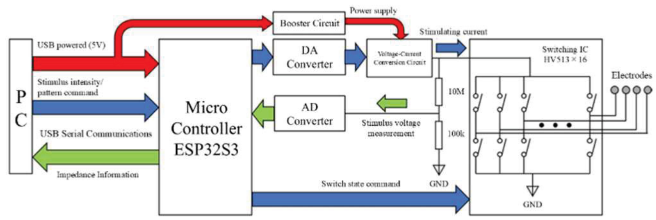

Fig. 2. Schematic diagram of the electro-tactile display

This electro-tactile display can switch between anodic stimulation, in which only one electrode serves as the anode while all others act as cathodes, and cathodic stimulation, in which only one electrode serves as the cathode while all others act as anodes. Neural activation induced by cathodic stimulation tends to produce pressure sensations [14]. Thus, this study employs only cathodic stimulation. For the pattern to be presented (in this case, a circular area), the electrodes along the circumference are identified and are then stimulated using cathodic stimulation. Note that the electrodes are not equally spaced for the circular presentation pattern, and the stimulated area in the experiment will not be a perfect circle.

III. Experiment

This study proposes a method to induce a sense of adhesion by modulating the timing and area of electrical stimulation in response to changes in finger pressure. To verify the effectiveness of the proposed method, experiments were carried out to assess the effects of stimulation timing and spatial extent on the perceived sense of adhesion. The study was approved by the Ethics Committee of the University of Electro-Communications (No. H24044).

Two experiments were carried out in this study. In Experiment 1, we investigated whether a sense of adhesion can be induced based on the *timing* of tactile presentation via electrical stimulation. In the context of pressing and lifting the finger from the adhesive surface, a continuous cutaneous sensation is generated during the lifting motion. This suggests that sense of adhesion perception can be elicited if electrical stimulation is applied to maintain continuous cutaneous sensation during finger lifting.

In Experiment 2, we investigated whether the sense of adhesion is more distinctly influenced by variations in the stimulated *area*. Previous studies have shown that the contact area on an adhesive surface is initially maintained during finger lifting before gradually decreasing. We examined whether electrical stimulation simulating this change would produce a more pronounced sense of adhesion.

A. Experiment 1: Condition

The purpose of Experiment 1 was to verify whether a sense of adhesion can be elicited by maintaining a cutaneous sensation when the fingers are lifted.

13 participants (11 males and 2 females, aged 21–24 years, 1 left-handed) took part in this experiment. All participants were provided with detailed information about the experiment and instructed to report any pain immediately. The experiment took approximately 15 minutes.

During the experiment, participants dried their fingertips with alcohol before putting on the finger cap to minimize variations in sensory perception. They were also instructed not to remove the finger cap once applied. However, if participants experienced difficulty perceiving electrical stimulation due to perspiration, they removed the finger cap, dried it with alcohol, and recalibrated the intensity of the electrical stimulation.

The stimulated area in this experiment was the outer edge of a circular region formed by the 20 electrodes shown in Fig. 3. This selection was based on the fact that the contact area approximates a circular shape when the fingertip touches the adhesive surface [6]. The inner area of the circle was not stimulated because skin strain tends to concentrate around the edges of the contact area. A previous study on presenting the sense of softness via electrical stimulation also employed peripheral stimulation of a circular area [3].

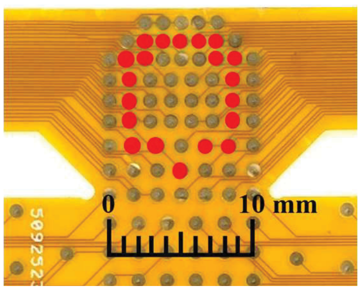

Fig. 3. Stimulated area in Experiment 1 (red dots)

Two experimental conditions were compared.

(1) Pull-up stimulation condition: electrical stimulation was applied to the designated area during the upward movement of the finger.

(2) Press-down stimulation condition: electrical stimulation was delivered to the designated area during the downward movement of the finger.

The stimulation timing for each condition is shown in Fig. 4. The pull-up stimulation condition corresponds to the phase where the pressing force decreases, while the press-down stimulation condition corresponds to the phase where the pressing force increases.

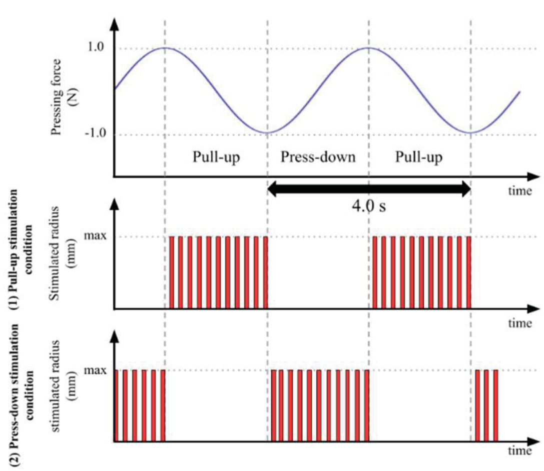

Fig. 4. Stimulation timing for each condition in Experiment 1

B. *Experiment 1: Procedure*

First, the intensity of the electrical stimulation was adjusted to clearly perceive the stimulation area without pain, and this adjusted pulse height was used in the subsequent experiments. However, if the participants experienced pain or difficulty perceiving the stimulation during the experiment, the pulse height was readjusted. The pulse width was fixed at 50 µs.

In the proposed method, the timing of electrical stimulation was determined based on changes in pressing force, identifying whether the finger was pulling up or pressing down. The participants practiced pressing their fingers before the experiment. They moved their fingers so that the pressing force varied from -1.0 N to 1.0 N at 0.25 Hz. They were instructed to move their fingers up and down vertically with the index finger of their dominant hand in the finger cap, as shown in Fig. 5. Under the experimental device, an ABS stand 5 cm high was placed so that the participants can move their fingers easily. The device, the stand, and the desk used in the experiment were fixed with double-sided tape. An LCD display in front of the participant showed a meter displaying the pressing force and a guide meter for movement control, allowing participants to adjust their finger movements accordingly.

Fig. 5. Pressing motion in Experiments 1 and 2. An ABS stand is placed under the experimental device to make it easier for participants to move their fingers, and it is fixed to the experimental device and the desk.

After the calibration and pressing practice, the participants moved their fingers up and down five times with the same movements as the practice. A stimulation pulse train was presented for each upward and downward movement, resulting in five stimulation pulse groups per trial. Participants then rated the perceived sense of softness and sense of adhesion on a 7-point Likert scale (1: not perceived – 7: distinctly perceived). The sense of softness was included in the evaluation because it is influenced by force perception and changes in contact area when interacting with an object, making it comparable to the sense of adhesion [16]. Preliminary experiments showed that the proposed method's sense of adhesion resembles the sensation of touching adhesive tape. Therefore, in the experiment, adhesion was explained to participants as “the sensation of being pulled by adhesive tape”.

Regarding pulling up and pressing down, the target and actual pressing forces were displayed on the screen as bars, as described above. Participants adjusted their pressing force to align the two bars as closely as possible. The system distinguished between pressing and lifting states in real-time based on changes in pressing force and delivered stimulation accordingly.

Ten trials were conducted, five sets for each condition in a random order. After the experiment, participants provided open-ended feedback.

C. Experiment 1: Result

The results of the experiment are shown in Fig. 6. The vertical axis represents the clarity of the presented tactile sensation, rated on a Likert scale. The data represent the mean responses for each condition, averaged over five trials per participant. A Wilcoxon signed-rank test was conducted on these data, revealing a significant difference in the clarity of the sense of softness between the two conditions ($p=0.01904$) and a highly significant difference in the clarity of adhesion ($p=0.0004883$).

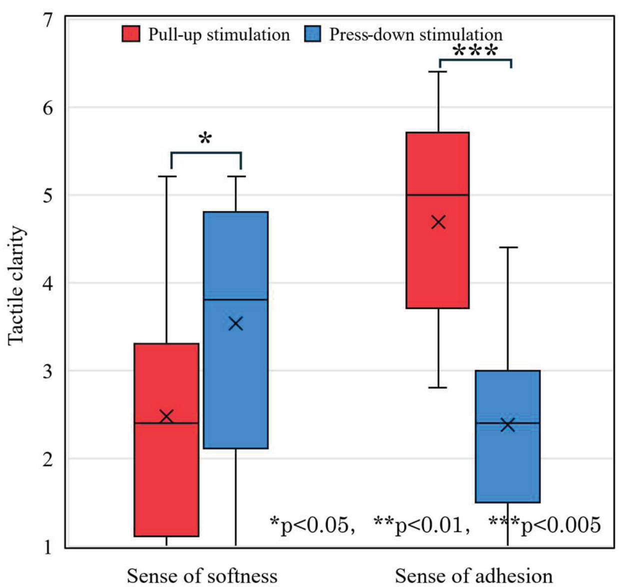

Fig. 6. Results of Experiment 1

D. Experiment 2: Procedure

The results of Experiment 1 demonstrated that a sense of adhesion can be induced by providing a cutaneous sensation during the finger-pulling motion. Experiment 2 aimed to investigate the effect of varying the stimulated area of the electrical stimulation, based on previous observations.

Ten participants (9 males and 1 female, aged 22–24 years, 1 left-handed) took part in the experiment. All participants were provided with detailed information about the experiment and instructed to report any pain immediately. The experiment took approximately 15 minutes.

As in Experiment 1, calibration and pressing exercises were conducted prior to the experiment and subsequent evaluations. As shown in Fig. 7, the stimulated area was a circular region formed by 24 electrodes. In this experiment, a wider area was stimulated than in Experiment 1 to enhance the perceptibility of the area change.

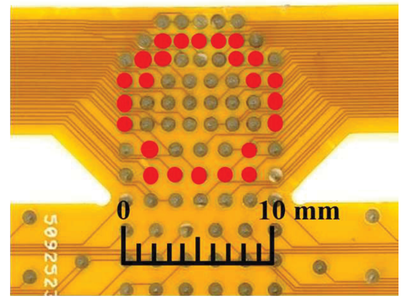

Fig. 7. Stimulated area in Experiment 2 (red dots)

Three experimental conditions were applied. Fig. 8 illustrates the stimulation area for each condition.

(1) Timing condition: Electrical stimulation was applied to a fixed area during the pulling-up motion, as in Experiment 1, pulling-up condition, without reproducing changes in the contact area on the adhesive surface.

(2) Area condition: Electrical stimulation was conducted to reproduce changes in the contact area on the adhesive surface, as described below.

(3) Timing & area condition: Electrical stimulation that reproduces changes in the contact area on the adhesive surface, as in (2), was applied, but only during the pulling-up motion.

Stimulation during pressing was omitted in the last condition (timing & area) because, in this experimental setup, the finger cap was pressed against the desk, physically increasing the perceived pressure. Therefore, adding electrical stimulation during this pressing period might not be necessary.

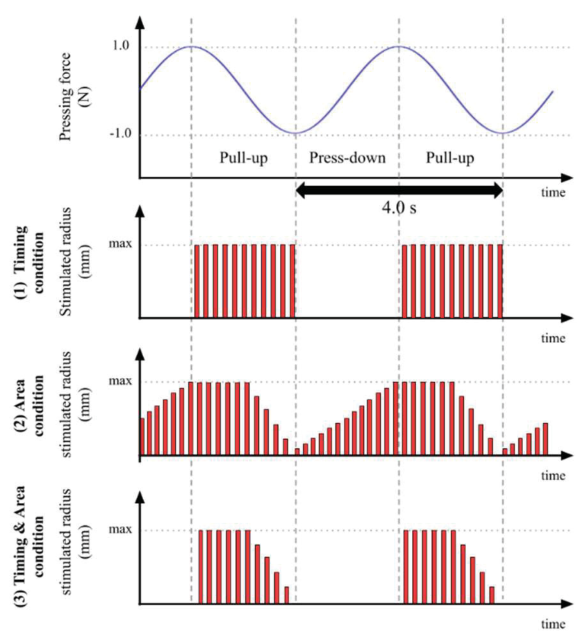

Fig. 8. Stimulated radius for each condition in Experiment 2

The change in stimulation area was modeled after the measurements by Yamaoka et al. [6]. Fig. 9 schematically illustrates their findings, showing the time-dependent changes in fingertip contact force and contact area when a fingertip comes into contact with an adhesive that had been cured for 120 minutes. These results indicate that the contact area starts to decrease one second after contact, signifying the onset of finger lifting. Additionally, at an intermediate point during lifting, the fingertip contact force becomes negative, suggesting that a sense of adhesion is perceived due to the generated pulling force. During this period, the contact area continues to decrease steadily. To replicate this phenomenon, we defined r_{UP} (0.0 ~ 1.0 cm) which is the radius of the stimulation area when pulling up at -1.0 ~ 0.0 N and r_{DOWN} (0.0 ~ 1.0 cm) which is the radius of the stimulation area when pressing down, were defined by Equations (1) and (2), where f (-1.0 ~ 1.0 N) represents the pressing force:

$$r_{UP} = 1.0 * f + 1.0 \quad (1)$$

$$r_{DOWN} = 0.5 * f + 0.5 \quad (2)$$

Also, the radius of the stimulation area when pulling up at 0.0 ~ 1.0 N was fixed at 1.0 cm.

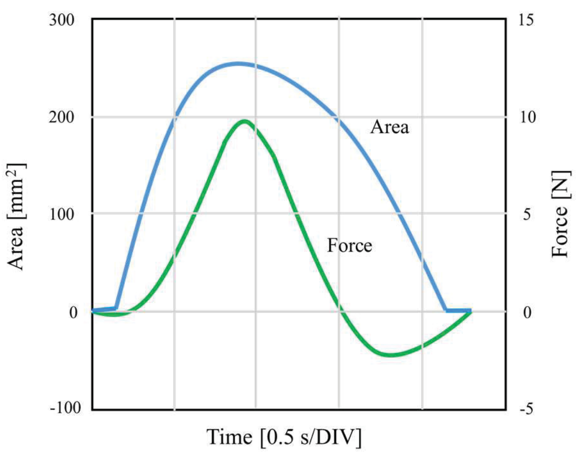

Fig. 9. Fingertip contact force and contact area following 120 minutes of adhesive curing (reconstructed from [6] by the authors)

Each condition was evaluated through 15 trials, with five sets per condition presented in a random order. After the experiment, the participants reported the clarity of both softness and adhesion, as in Experiment 1. Additionally, they provided open-ended feedback.

E. *Experiment 2: Result*

The results are shown in Fig. 10. The vertical axis represents the clarity of the presented tactile sensation, rated on a Likert scale. The data represent the average responses for each condition across five sets per participant. The Friedman test was applied to the data, revealing significant differences for the clarity of softness (p=0.017) and the clarity of adhesion (p=0.030). The Wilcoxon signed-rank test with Bonferroni correction showed significant differences between the timing & area conditions for the clarity of sense of softness (p=0.030) and clarity of sense of adhesion (p=0.042).

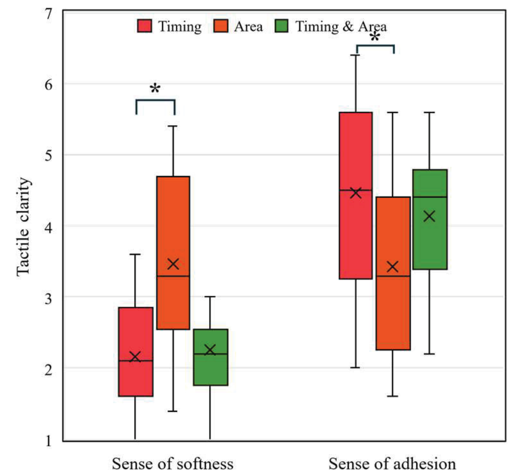

Fig. 10. Results of Experiment 2

IV. Discussion

A. *Experiment 1*

The experimental results showed that the sense of adhesion was perceived more clearly in the pull-up stimulation condition than in the press-down stimulation condition. Nine participants reported perceiving a sense of adhesion like touching an adhesive tape when the stimulation was presented during the pull-up condition. However, four participants did not perceive a sense of adhesion and felt that it was just electrical stimulation.

The sense of softness was perceived more strongly in the press-down stimulation condition than in the pull-up stimulation condition. This result is similar to a previous study that reproduced the change in contact area during pressing through electrical stimulation [3]. However, four participants mentioned that they did not feel a sense of softness and that the electrical stimulation masked this sensation. In Experiment 1, no change in contact area was presented during pressing, so it is likely that participants perceived softness differently than how they typically perceive it through changes in contact area. One possibility is that, by presenting a constant stimulation during pressing, the participants interpreted the "unchanging skin sensation despite increasing pressing force" as "soft".

Additionally, three participants reported that the pressure sensation caused by the finger cap inhibited tactile perception, and that their fingernails hit the back of the cap, preventing stimulation from reaching the entire fingertip. This suggests that both the sense of softness and adhesion may be inhibited by the tactile sensation caused by the finger cap itself, and that future designs should allow greater flexibility for the fingertips.

Some participants also mentioned feeling a sense of resistance due to the movement of the target pressing force value visually displayed on the monitor during the experiment. This suggests that an unintended pseudo-haptic effect may have been induced, and it may be necessary to conduct future experiments without visual indicators. Conversely, since vision greatly influences the sense of touch, it is important to consider presenting a more effective sense of adhesion through devices like VR headsets.

B. Experiment 2

In this experiment, unlike Experiment 1, we aimed to present a higher-quality sense of adhesion by simulating a change in contact area, based on actual measurement results from previous research, instead of relying solely on the ON/OFF timing of stimulation. However, the experimental results did not align with this expectation.

The results showed that the clarity of the sense of adhesion was significantly higher in the timing condition compared to the area condition, suggesting that the timing of tactile stimulation during the pulling-up phase is more important than replicating the change in contact area when presenting the sense of adhesion through electrical stimulation. However, it should be noted that in this experiment, participants were asked to rate the 'clarity' of the sense of adhesion. Faithfully reproducing the change in contact area may contribute to the realism of the sense of adhesion, but not necessarily to its clarity.

Additionally, the present experiment does not account for the "pressure sensation physically produced by pressing." In the current experimental setup, where the finger cap is pressed against the ground, physical pressure naturally generates cutaneous sensations. It is possible that the electrical stimulation should have accounted for the physically generated cutaneous sensations, presenting only the missing "difference."

Regarding the clarity of the sense of softness, the area condition was found to be significantly clearer than the timing condition. In the area condition, the stimulation area increased as the pressing force increased during pressing. This is consistent with a previous study on presenting the sense of softness using electro-tactile displays [3], supporting the validity of the result.

However, eight participants did not perceive a change in the stimulation area during the experiment. Six of them interpreted the differences between conditions as variations in stimulation duration. The results showed that the clarity of the sense of adhesion was higher in the timing condition, where the stronger stimulation lasted longer. Cathodic electrical stimulation is known to be more likely to produce pressure sensations than anodic stimulation, but less likely to produce sensations with high spatial resolution. If this is why the perception of distinct area changes was disturbed, further studies including anodic stimulation may be necessary.

Additionally, two participants mentioned that the perception of adhesion was inhibited because the finger movements were not intuitive. Indeed, the action of pressing the finger ends against the ground and moving them vertically may not have felt natural. This suggests that the electro-tactile display can either be mobile or fixed, but with enough flexibility for the user to easily change the angle of their fingers.

V. Conclusion

In this study, we proposed and evaluated a presentation method using an electro-tactile display attached to the fingertip, aiming to realize a compact way to present the sense of adhesion. In Experiment 1, we verified the presentation of the cutaneous sensation during the pulling force on the adhesive surface, and found that a clear sense of adhesion was produced. In Experiment 2, we verified a method to reproduce changes in the contact area of the skin with the adhesive by electrical stimulation, and found that the change in contact area contributes little to the sense of adhesion, at least in the current setup.

The results of this research can be used for realistic tactile representation of an object with a sense of adhesion, such as human skin, as described in the Introduction. On the other hand, the sense of adhesion can also be seen as a force that can be used to achieve force sensation presentation in the direction of pulling up a finger with a wearable haptic device. In other words, this research can be considered as a kind of proposal of a new method of wearable force sensation presentation.

In our next step, we aim to present a high-quality sense of adhesion, and will, for example, conduct a matching task using adhesive tapes with different adhesive strengths as real samples, while also incorporating visual stimulation in a VR environment. Additionally, electrical stimulation can represent not only the contact area but also the intensity of the sensation by adjusting the pulse height. By utilizing this feature, we will investigate the possibility of simulating the force sensation without fixing the device to the desk, by using electrical stimulation to reproduce changes in the pulling force during the pull-up.

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