Double-sided Printed Tactile Display with Electrical Stimuli and Electrostatic Forces and its Assessment

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ABSTRACT

Humans can perceive tactile sensation through multimodal stimuli. To demonstrate realistic pseudo tactile sensation for the users, a tactile display is needed that can provide multiple tactile stimuli. In this paper, we have explicated a novel printed tactile display that can provide both the electrical stimulus and the electrostatic force. The circuit patterns for each stimulus were fabricated by employing the technique of double-sided conductive ink printing. Requirements for the fabrication process were analyzed and the durability of the tactile display was evaluated. Users' perceptions of a single tactile stimulus and multiple tactile stimuli were also investigated. The obtained experimental results indicate that the proposed tactile display is capable of exhibiting realistic tactile sensation and can be incorporated by various applications such as tactile sensation printing of pictorial illustrations and paintings. Furthermore, the proposed hybrid tactile display can contribute to accelerated prototyping and development of new tactile devices.

Author Keywords

Tactile display; double-sided printing; conductive ink; multiple stimuli; electrical stimulus; electrostatic force.

ACM Classification Keywords

H.5.2. Information Interfaces and Presentation (e.g. HCI): User Interfaces Input Devices and Strategies.

INTRODUCTION

Human skin possesses several types of mechanoreceptors that respond to tactile stimuli, allowing us to perceive touch [15]. The density of mechanoreceptors varies according to type and location, and they are most dense in the fingertips, which contact objects most frequently. Tactile displays, which artificially provide touch sensation to humans, have been studied for several decades.

To further develop tactile displays, there are several technical hurdles to overcome. For example, it is necessary to fabricate actuators, which need to be integrated into the electronic circuits. Additionally, to present a rich tactile sensation, multiple stimuli should occur simultaneously, because humans perceive a combination of sensations at once. Most studies present tactile displays that provide only a single tactile stimulus at a time. However, a few groups have presented tactile displays that produce multiple simultaneous stimuli. Nevertheless, there has been insufficient research into how humans perceive simultaneous multiple tactile stimuli.

In this paper, we propose a hybrid tactile display that can simultaneously provide an electrical stimulus and an electrostatic force. We also fabricate the tactile display using a double-sided inkjet printing technique. Both types of stimuli require only electrodes and a power supply for stimulation. Additionally, the electrodes can be easily integrated into thin paper or a polyethylene terephthalate (PET) substrate, using inkjet-printed conductive ink. Electrode patterns are easily designed with illustration software such as Adobe Illustrator, and can be quickly printed. Our prototyping technique enable easy and inexpensive fabrication of the experimental device and facilitates future work in the haptics field. The printed circuit patterns are connected to a high voltage power supply and produce tactile stimuli with periodic voltage, which provides vibration and electrostatic force to modulate frictional sensations. Thus, our proposed tactile display can simultaneously present both vertical vibration and horizontal frictional force. The results of our evaluation show that tactile sensation is influenced by the interaction between electrical stimulus and electrostatic force with various frequency conditions. Proposed hybrid tactile display using an electrical stimulus and an electrostatic force presents a more realistic tactile presentation that has richer information than tactile feedback with a simple stimulus.

The contributions of this paper are as follows:

1. We examined the characteristics of tactile sensation while applying electrical stimulus and electrostatic force.
2. We consider a prototyping technique with double-sided inkjet printing to fabricate hybrid tactile display which would be useful in subsequent haptics research.
3. We investigate how humans feel tactile sensations using our hybrid tactile display.

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4. We show several potential applications using our hybrid tactile display.

RELATED WORK

Tactile Display

In the human skin, mechanoreceptors such as Meissner's corpuscle, the Ruffini corpuscle, the Pacinian corpuscle, and the Merkel disc contribute to tactile perception [15]. Mechanoreceptor characteristics have been studied widely, and it is known that each type responds to different kinds of tactile stimuli.

Tactile displays, which provide tactile sensation to users, have been extensively developed and a variety of techniques have been considered. For example, there are methods that use actuators and vibrations [4, 5, 22], string tension [1], pneumatic actuators [32, 34], and direct skin deformation with a changing surface [8, 33, 43]. There are other examples that do not use mechanical actuation. For example, ultrasonic radiation [13, 24] and thermal energy of a plasma arc [36] have been effective.

Mechanically-driven tactile displays require actuators, whereas those that operate via electrodes do not. Strong et al. developed a tactile display that modulates frictional force using electrostatic force between fingertip and electrodes [37]. Bau et al. proposed TeslaTouch [7], which integrates an electrostatic tactile display with a touchscreen. It adds tactile feedback to displayed screen images. Bau et al. also proposed a type of electrostatic force method, called *Reverse-Electrovibration (REVEL)* [6]. A user's hand is connected to high voltage, and conductive objects coated with an insulation layer are connected to GND. This allows users to perceive modulated textures using a device worn on the hand. Directly changing the perceived texture of objects via a human fingertip can be provided by integrating the methods of TeslaTouch and REVEL.

However, these methods are strongly affected by environmental conditions (e.g., finger perspiration). Yamamoto et al. developed another type of tactile display for thrust force using electrostatic force [40]. The tactile display consists of two sheets, and users can perceive electrostatic force through one of them. This method allows users to operate without the affectations of environment and fingertip conditions. Nakamura et al. developed a tactile display using electrostatic force for multi-finger stimulation [26]. Their display consists of a grounded electrode and a finger pad connected to high voltage. Frictional force to the finger pad is modulated by electrostatic force. In our study, we apply a pad-type structure to a multiple-tactile display to reduce the damping effects of dirty fingertips.

Electrical stimulation of the nerves inside skin requires only a current and electrodes [38]. Kajimoto developed a cylindrical electrical tactile display to stimulate the human palm, using many electrodes [16]. Kitamura et al. fabricated a needle-type electrical tactile display with a micro-fabrication process [21]. Their displays provide electrical stimulus with low voltage applied directly to the dermis.

Nearly all the described tactile displays provide a single tactile stimulus. However, humans perceive tactile sensations via a combination of signals from the skin's mechanoreceptors. Therefore, multiple tactile stimulation is necessary for a rich tactile sensation to reproduce the tactile feedback of a real object surface. Only a few studies focus on multiple tactile sensations. Yem et al. developed a tactile display called "FinGAR," which can stimulate optional mechanoreceptors with electrical stimuli, mechanical frictional forces, and vibrations [42]. They investigated how users perceive tactile sensations via multiple stimuli. Pyo et al. developed a tactile display using vibration and frictional force with two electrostatic actuators [31]. Murakami et al. integrated a belt-type tactile display for pressure, shear force, and vibration using a Peltier element to create hybrid tactile stimulation [25]. Most of the previous hybrid tactile diplays aimed to stimulate only one fingertip owing to the bulk of electronic parts or circuits such as actuators and motors. Our study addresses this limitation by examining the novel hybrid tactile display using electrical stimulus and electrostatic force.

Yang et al. integrated four motors and a peltier element into a hybrid tactile dsiplay [41]. The tactile display was able to present a combination of vibration stimulus and thermal stimulus. Jimenez et al. also developed hybrid tactile display using vibration and thermal sensations. They developed a system for prosthesis users which consited of a tactile sensor and a multiple tactile display [14]. The obtained tactile sensation from the tactile sensor was presented to the upper-arm of the user using a force, vibration and thermal tactor. Gallo et al. fabricated a tactile display for heat stimulus and bump stimulus with micro-fabrication process [9]. Gallo et al. aimed to realize flexible hybrid tactile display that are capable of matching the skin's curvature.

In this paper, we propose a novel technique to realize a hybrid tactile display with multiple stimuli, leveraging electrical stimulus and electrostatic force. The proposed tactile display only requires small electrodes, which can be easily integrated in a thin substrate and miniaturized. Additionally, conductive inkjet printing combined with design by illustration software enables the fabrication of a variety of tactile devices that can be custom fit to the user's hand or body and applied to a wide range of practical and experimental uses. The electrodes can be fabricated using a flexible substrate such as paper or PET film, which is advantageous to not only whole-hand stimulation but also to tactile stimulation with high resolution. We fabricated a tactile display with conductive printing ink and evaluated perceived tactile sensation through the display.

Conductive Ink

In recent years, there have been many studies utilizing conductive ink with inkjet printing. In human computer interface fields, this technique is useful for prototyping circuits and sensors, and for creating interfaces. For example, Kawahara et al. proposed a method to print circuit patterns designed with illustration software [20]. Their method allows users to prototype electrical circuits using a commercial inkjet printer. After Kawahara et al. proposed their study [20], many other studies about sensor fabrication were proposed [10, 11, 12, 17, 29].

Olberding et al. printed circuit patterns on a phosphor and dielectric layer to create a lighting touch screen [28]. Olberding et al. applied this technique to produce a variety of interactions [30]. Li et al. proposed applications with printed radio frequency identification tags [23]. Nakahara et al. developed a paper-based robot with a phase change actuator, in which liquid in a bag was vaporized with a printed heater, causing pressurization and actuation [27]. Other studies printed circuit patterns on single-sided paper to interface applications for capacitive touchscreens [18, 44]. However, there are other proposed studies to use double-sided printing techniques [2, 39].

Nonetheless, inkjet printing has not been applied to haptic devices. In this study, we use conductive ink to fabricate a tactile display for multiple tactile stimulation, and we clarify printing requirements.

PRINCIPLE OF THE PROPOSED TACTILE DISPLAY

In this section, we present the construction technique and principle of each hybrid tactile display using electrical stimulus and electrostatic force.

Electrostatic Force Tactile Display

Electrostatic force stimulation results from electrostatic force between two charged conductors. One conductor is connected to high voltage and the other is connected to GND. An insulator is put on one conductor and two others are electrically disconnected. When two conductors touch, they charge oppositely and electrostatic force affects each capacitor. When one conductor is moved across another fixed conductor, the frictional force is increased. Thus, users can perceive touch friction. Tactile sensations, such as vibration, can also be presented using periodic electrostatic forces.

Electrostatic force is categorized into direct and indirect types [26]. The direct type provides electrostatic force directly to the skin. The indirect type applies electrostatic force to a moving conductor. Figure 1-upper left shows the basic structure of each. The direct type utilizes the finger as a conductor. This is advantageous because the direct type only requires one conductor covered with an insulator for stimulation. Sometimes, when a dirty finger directly touches the insulator it causes unstable tactile stimulation [6]. In contrast to the direct type, the indirect type provides electrostatic force along a moving electrode presenting a stable tactile stimulus to users regardless of their finger conditions [26]. To develop a hybrid tactile display using both electrical stimulus and electrostatic force, we leveraged the indirect type of electrostatic force and affix each electrode to the front and back surfaces of a flexible substrate.

Electrical Stimulus Tactile Display

Electrical stimulus is a tactile presentation method that stimulates nerves inside skin using current flow between two electrodes (Figure 1-bottom left). One electrode is connected to high voltage and the other is grounded. When the users touch on the electrodes with their finger, current flow is induced inside the skin. Voltage potential is caused instantly and the skin's mechanoreceptors are stimulated. As a result, users perceive vertical vibration on the fingertip.

Proposed hybrid tactile display is implemented both tactile display on the one substrate sheet (Figure 1-right).

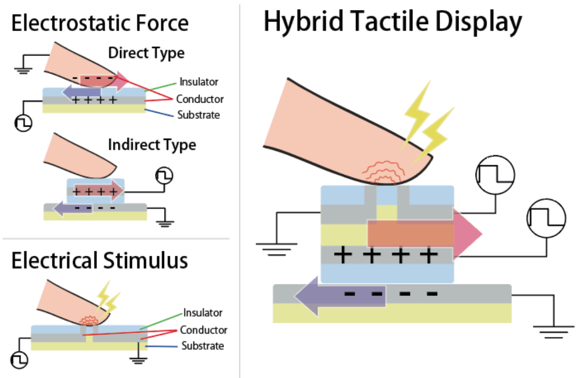


Figure 1. Electrostatic force tactile display (upper left), electrical stimulus tactile display (bottom left), and hybrid tactile display (right).

IMPLEMENTATION

The requirements for the proposed hybrid tactile display are described as follows.

1. The tactile display consists of bare electrodes for electrical stimulation.

2. The tactile display consists of an electrode covered with an insulator to generate electrostatic force.

In this study, we applied a indirect type structure for electrostatic force. To maintain the sensation of touching an object directly, the distance between fingertip and objects should be minimized. To satisfy this requirement, we propose a fabrication technique of the hybrid tactile display with conductive ink printing on thin substrate.

Figure 2-left shows the basic structure of the proposed tactile display. Electrode patterns are printed on a paper substrate, providing the electrical stimulus tactile display, as shown in Figure 2-top right. The patterns have two circular electrode pads for stimulation. Wires connected to the pads are covered with commercial tape to avoid direct contact with the skin. The central electrode is connected to GND. Other electrodes are connected to high voltage. When users touch electrodes with their finger pad, they perceive spatial vibration or pressure between the stimulated electrodes.

An electrostatic tactile display is also formed on the opposite side of the display, as shown in Figure 2-bottom right. The electrode dimensions are 10 × 10 mm, and are covered with a commercial tape for insulation. The electrode is connected to high voltage with a wire. In actual operation, the bottom side of the substrate is slid opposite the grounded objects. Thus, users can perceive friction or vibration sensations between the electrode and the object.

The inkjet printer is a Brother, MFC-J840N. Its printer tank is filled with conductive ink (Mitsubishi Paper Mill, NBSIJ-MU01). The circuit patterns are printed on a special paper with a thickness of 270 μm. An insulating layer is formed with commercial tape on several electrodes. Voltage is applied to each electrode with a high voltage power supply (MHV 12-1.0K2000P, Bellnix Co., Ltd), which is controlled with a microcomputer (mbed LPC 1768, ARM Ltd). Maximum peak voltage is 600 V. We implemented the system with a laptop graphical user interface (GUI), which can control the peak voltage (50V to 600V) and frequency (1 Hz to 640 Hz).

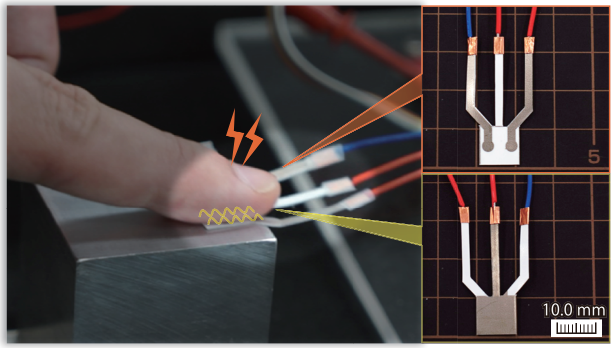


Figure 2. Basic structure of the double-sided printed hybrid tactile display. The surface side: electrode pattern for electrical stimulus (top right). The back side: electrode pattern for electrostatic force (bottom right).

Design of the Electrodes Pattern

In this section, we discuss electrode pattern designs for providing electrical stimulation and electrostatic force. First, we investigate the size and distance of electrodes for electrical stimulation. To apply the tactile sensation with wide range of human skin, the electrode pads should be integrated as densely as possible. However, electrode size and density are limited by the printer accuracy, and hence, the small electrodes and thin wires can sometimes break. To optimize the arrangement of the electrode pad and wiring, it is conceivable to utilize interconnection techniques of the printed electrodes [2, 39].

However, our method uses both surfaces of the paper substrate for two independent tactile displays. Additionally, such interconnection techniques require manual implementation, such as using a stapler with metal pins. This is not suitable for high-density electrodes; stable electrostimulation requires larger electrode pads. Thus, the diameter of our electrode pad is 1.0 to 3.0 mm; electrode wiring width is 0.5 to 1.0 mm; and the separation between the electrode pads is 1.0 mm.

Next, we investigate the size of electrodes for electrostatic properties. Electrostatic force is estimated using the model of a parallel plate capacitor [26]. Thus, the contact area of the electrode pattern is an important factor for electrostatic force control. We apply the indirect type structure to the proposed tactile display, because it is effective at ignoring fingertip conditions. To maximize the active area, our electrode is 10 × 10 mm: enough to cover the entire finger pad.

Durability of the Inkjet Printed Electrodes

Because of printing, the durability of the tactile display is lower than that of a circuit board or indium tin oxide (ITO) electrode. When printed electrode pads and wires break, they can be repaired via repainting with a conductive ink pen. However, those areas build up resistance, causing the intensity of electrical stimulus or electrostatic force to change. When developing applications, users should carefully design circuits to avoid bending and scratching. Moreover, conductive ink deteriorates with time and is not suitable for long-term use. Because our electrodes and wires are partially covered with tape, they gain added protection from these external threats. However, skin can directly contact parts of the bare electrodes, causing damage from frictional force and dirt. To evaluate the durability of the circuits, we conducted durability tests in working conditions.

Preliminary Evaluation: Electrodes Durability

In this evaluation, we applied AC voltage to the electrodes and measured resistance change over time. Figure 3 shows the experimental setup. The circuit pattern has two circular electrode pads with a diameter of 1.0 mm (the minimum). A central electrode is connected to GND with a wire, and the other electrode is connected to high voltage. The wire parts are covered with tape for insulation. To quantitatively evaluate electrode degradation, we covered two electrode pads with conductive gel (Fukuda Denshi Co., Ltd., TEO-174DCR) to emulate active use. The resistance of the gel is less than 2 KΩ, having similar electrical characteristics as human skin.

The current flows between the two electrode pads, *e to f* through the gel. Terminal electrodes *b* and *c* are formed to measure resistance of each electrode. We measured the resistance of both electrode pads (between *a* and *b*, *c* and *d*). We applied AC voltage and measured the resistance every 10 minutes. The peak voltage was 500 V and frequency was 100 Hz.

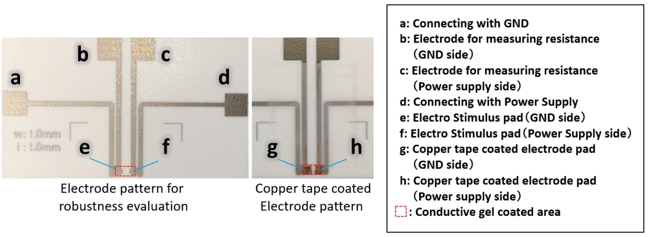


Figure 3. Experimental setting of electrodes durability evaluation.

Result and Discussion

As shown in Figure 4-top left, the resistance of the electrode connected to high voltage was almost constant for 30 minutes, and then it increased. The electrode broke after 40 minutes. In contrast to high voltage, the resistance of the electrode connected to GND voltage did not change.

We confirmed that the bare electrode pads connected to high voltage were darkened (Figure 4, bottom center) because of contact with the gel (one reason for the destruction).

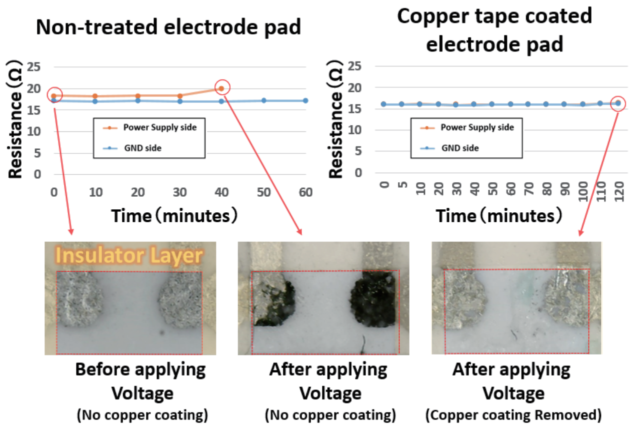


Figure 4. Results of electrodes durability evaluation.

To protect the bare electrodes from the gel, we coated the electrode pads with copper tape. We conducted the durability evaluation again, this time with the covered electrodes (3 *g,h*). As shown in Figure 4-top right, the resistance of each electrode pad was constant for 50 minutes. We continued the experiment for 2 hours and confirmed that the resistance was not changed. After the experiment, we removed the copper tape and carefully observed the electrodes. They were not discolored (Figure 4, bottom right).

From the experimental results, the copper tape coating effectively improved the durability of the electrode pads. Notably, when the user touched the bare electrodes for tactile stimulation, the electrodes were discolored. We conclude that certain physical property changes occur when finger perspiration and high voltage are combined.

USER STUDY

In this section, we describe two evaluations conducted to reveal how users perceive the proposed tactile stimulus. It is well-known that tactile sensation caused by electrostatic force and electrical stimulus changes with applied voltage. However, this has not been tested for hybrid tactile displays. Both electrostatic force and electrical stimulus frequencies can be changed from 1 Hz to 640 Hz by our system. However, it is difficult to evaluate all combinations. Thus, we evaluated the detectable frequency differences of each stimulus and conducted experiments with a combination of the detected stimuli.

Evaluation 1: Range of Detectable Frequency Difference

We conducted experiments to clarify the range of detectable frequency differences of each stimulus by the user.

Task

Electrical stimulus or electrostatic force was presented to the participants, and we asked them to pick the matching stimulus from a list. Participants placed an index finger on the center of the tactile display. The experiment was conducted using a laptop computer, controlling the tactile stimuli. Participants controlled GUI operations with their free hands. When the participants pressed a "sample button" or "answer buttons," the tactile stimulus was provided to the users. The participants then selected a stimulus that they felt similar to the sample stimulus from the answer list. The participants repeated the task until they had evaluated all stimuli. We chose nine parameter conditions (1 Hz, 5 Hz, 10 Hz, 20 Hz, 40 Hz, 80 Hz, 160 Hz, 320 Hz, and 640 Hz) as the frequencies of electrostatic force (f_{sta}).

We also chose 10 parameter conditions (1 Hz, 5 Hz, 10 Hz, 20 Hz, 40 Hz, 80 Hz, 100 Hz, 160 Hz, 320 Hz, and 640 Hz) as the frequencies of electrical stimulus (f_{sti}). One session of electrostatic force evaluation consisted of a random order of 9 parameter conditions × 5 actual trial + 3 practice trial = 48 answers/participant.

One session of electrical stimulus evaluation consisted of a random order of 10 parametric conditions × 5 actual trial + 3 practice trial = 53 answers/participant. Frequencies were presented in a random order, as were the answer buttons, so as to avoid estimations of the frequency based on the position of the answer buttons. We then instructed the participants to try all presented stimuli at least once before choosing an answer.

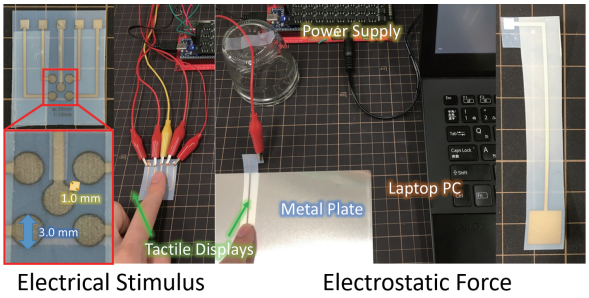


Figure 5. Experimental setting of evaluation 1.

Figure 5 shows the experimental setting and actual electrode pattern on a PET substrate (Mitsubishi Paper Mill, NB-TP-3GU100). In the experiment for electrostatic force, we printed a 10.0 × 10.0 mm electrode pattern on a PET substrate sheet. The participants slid the sheet on a grounded metal plate to receive the stimulus. In the experiment for electrical stimulus, we printed five electrode patterns on a PET substrate sheet. Several patterns have 3.0 mm diameter electrode pads for stimulation. The central electrode was connected to GND and others were connected to high voltage. To avoid electrode deterioration, we used a new sheet for each trial, and we replaced the sheet whenever we observed electrode discoloration. Eight volunteers participated in the experiment (electrostatic force: eight males; average age: 23.6 years, *SD*: 1.80, electrical stimulus: eight males; average age: 23.5 years, *SD*: 1.87).

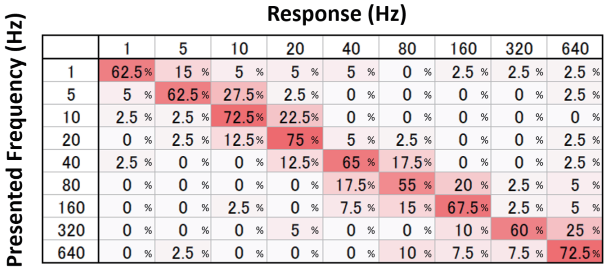
Result and Discussion

Experimental results are shown in Table 1 and 2. The participants were able to discriminate the stimulus under almost all experimental conditions of electrostatic force. However, the average rate of correct answers is 65 % (*SD*: 6.23): not high accuracy. The low recognition rate was the result of the narrow intervals of each selected frequency. We expect the discrimination rate to improve with wider intervals. Thus, we selected four frequency (5 Hz, 20 Hz, 80 Hz, and 320 Hz) by skipping every other frequency from the parameters using in this evaluation to improve the discrimination rate in Evaluation 2.

Although the recognition rate for the electrical stimulus was also low, but participants were able to sufficiently distinguish between the “low frequency” and “high frequency” electrical stimulus used in this evaluation. When the electrical stimulus with the low frequency (1 Hz, 5 Hz, and 10 Hz) was applied, participants rarely selected the high frequency (100 Hz, 160 Hz, 320 Hz, and 640 Hz). The participants also did not select the low frequency stimulus when the stimulus with high frequency was applied.

We assume that they could roughly discriminate between the electrical stimulus with low and high frequencies. Thus, we selected high frequency (640 Hz), low-frequency (10 Hz), and middle frequency (80 Hz).

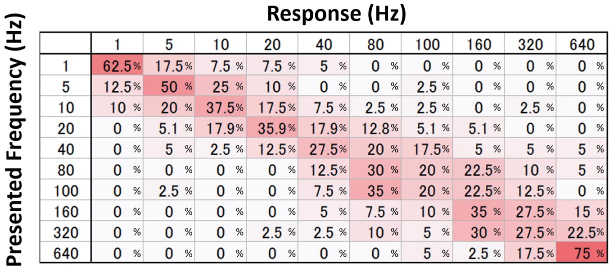
Table 1. Results of the recognition accuracy of electrostatic force sensations.



Response (Hz)

Presented Frequency (Hz)	1	5	10	20	40	80	160	320	640
1	62.5%	15 %	5 %	5 %	5 %	0 %	2.5 %	2.5 %	2.5 %
5	5 %	62.5%	27.5%	2.5 %	0 %	0 %	0 %	0 %	2.5 %
10	2.5 %	2.5 %	72.5%	22.5%	0 %	0 %	0 %	0 %	0 %
20	0 %	2.5 %	12.5%	75 %	5 %	2.5 %	0 %	0 %	2.5 %
40	2.5 %	0 %	0 %	12.5%	65 %	17.5%	0 %	0 %	2.5 %
80	0 %	0 %	0 %	0 %	17.5%	55 %	20 %	2.5 %	5 %
160	0 %	0 %	2.5 %	0 %	7.5 %	15 %	67.5%	2.5 %	5 %
320	0 %	0 %	0 %	5 %	0 %	0 %	10 %	60 %	25 %
640	0 %	2.5 %	0 %	0 %	0 %	10 %	7.5 %	7.5 %	72.5%

Table 2. Results of the recognition accuracy of electrical stimulus sensations.



Response (Hz)

Presented Frequency (Hz)	1	5	10	20	40	80	100	160	320	640
1	62.5%	17.5%	7.5 %	7.5 %	5 %	0 %	0 %	0 %	0 %	0 %
5	12.5%	50 %	25 %	10 %	0 %	0 %	2.5 %	0 %	0 %	0 %
10	10 %	20 %	37.5%	17.5%	7.5 %	2.5 %	2.5 %	0 %	2.5 %	0 %
20	0 %	5.1 %	17.9%	35.9%	17.9%	12.8%	5.1 %	5.1 %	0 %	0 %
40	0 %	5 %	2.5 %	12.5%	27.5%	20 %	17.5%	5 %	5 %	5 %
80	0 %	0 %	0 %	0 %	12.5%	30 %	20 %	22.5%	10 %	5 %
100	0 %	2.5 %	0 %	0 %	7.5 %	35 %	20 %	22.5%	12.5%	0 %
160	0 %	0 %	0 %	0 %	5 %	7.5 %	10 %	35 %	27.5%	15 %
320	0 %	0 %	0 %	2.5 %	2.5 %	10 %	5 %	30 %	27.5%	22.5%
640	0 %	0 %	0 %	0 %	0 %	0 %	5 %	2.5 %	17.5%	75 %

Evaluation 2: Sensational Experiments

In this section, we describe the evaluation of how the participants experience the sensations presented by a hybrid tactile display using electrical stimulus and electrostatic force. We based our tests on Bau’s experimental procedures [7].

Task

We requested the participants to experience our hybrid tactile display with 20 parameter conditions, and they answered a three-section questionnaire about tactile sensations. The participants were able to move the tactile display on a grounded metal plate freely. We provided the electrical stimulus, electrostatic force, and hybrid tactile stimuli in random order. Tactile stimulus was controlled by our experimental system. Stimulation consisted of the repetition of 2 seconds at 2 seconds intervals. The participants were required to answer the questionnaire during each trial.

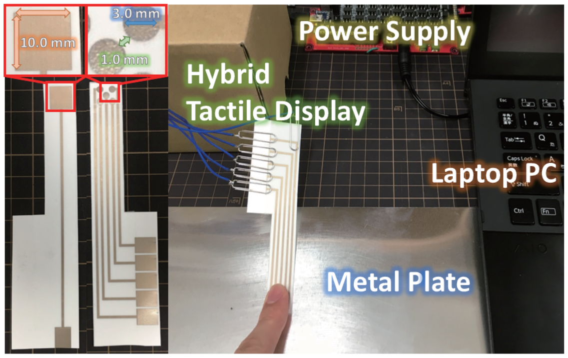


Figure 6. Experimental setting of evaluation 2.

In the first section, the participants described the tactile sensations in their own words. In the second section, participants selected the real object having similar tactile sensations to the presented stimulus. In the final section, participants rated seven different sensations (selected from related works) on a seven-point Likert scale (“sticky,” “frictional,” “bumpy,” “touch,” “temperature,” “hardness,” and “pleasant”). Presented different sensation S_{1-7} was selected from related works [3, 7, 35].

For the above procedure, we presented the combination of five electrostatic force parameter conditions (f_{sta} = 5 Hz, 20 Hz, 80 Hz, 320 Hz, and *no* f_{sta} *stimulus*) and four electrical stimulus parameter conditions (f_{sti} = 5 Hz, 80 Hz, 640 Hz, and *no* f_{sti} *stimulus*). In Evaluation 1, we selected more detailed frequency conditions than examined in previous studies in an attempt to determine the discriminable frequency conditions that can be distinguished by users. The same voltage was applied to both tactile displays.

The hybrid tactile stimulation $f_h[f_{sta}, f_{sti}]$ was a combination of each stimulus condition; a total of 20 combinations were provided to the subjects in random order. On the surface of the sheet, electrodes for electrical stimulus were printed. On the back side, electrodes for electrostatic force were printed. To avoid the effect of the deterioration of electrodes, we replaced the sheet for each trial, and whenever we observed discoloration of the electrodes. Eight volunteers participated in the experiment (two females and six males; average age: 23.0 years, *SD*: 1.80).

Results and Discussion

We analyzed the data via repeated analysis of variance (ANOVA) measures and the Bonferroni post hoc test. Consequently, we observed the main effects of f_h ($F_{19,133}$ = 7.97, $p < 0.001$). We also observed significant interaction between S and f_h ($F_{144,798}$ = 2.70). With the combination of the S and f_h, S_1 had a significant difference between f_{sti} = 10 Hz only and f_h*[5 Hz, 10 Hz]*, f_{sti} = 10 Hz only and f_h*[5 Hz, 80 Hz]*.

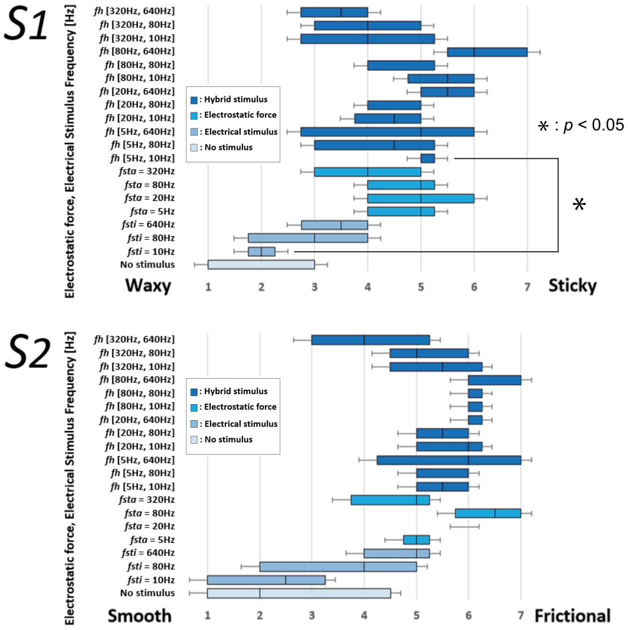


Figure 7. Result of the sensational evaluation of S_1 and S_2.

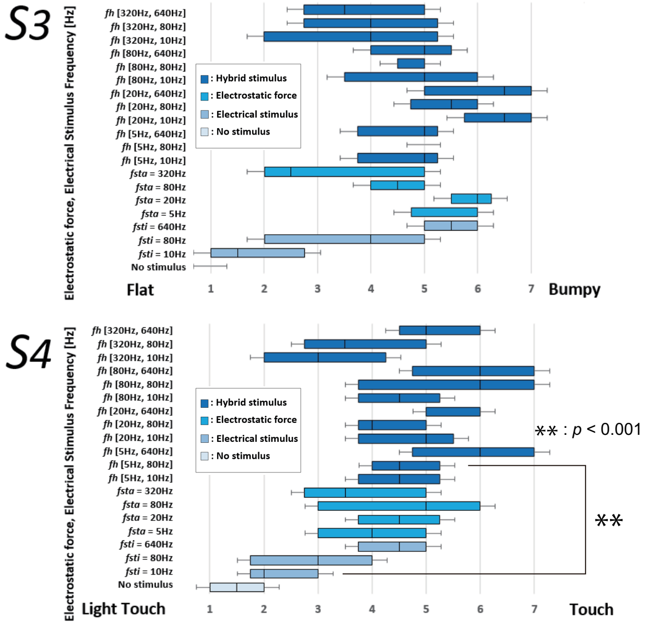


Figure 8. Result of the sensational evaluation of S_3 and S_4.

Sticky (S1) and Frictinoal (S2) Sensation

As shown in Figure 7, similar tendencies are confirmed for sticky and frictional sensations. When we did not apply both stimuli, participants felt “waxy/smooth” (S_1 and S_2 were mapped at the left side of the graph). Next, S_1 and S_2 were increased as f_{sti} increased. When only f_{sti} stimulus was applied, S_1 and S_2 were mapped in the range from “waxy/smooth” to “neutral.” When only f_{sta} stimulus was applied, S_1 and S_2 were mapped in the range from “neutral” to “sticky/frictional.”

To analyze the results in detail, we divided f_{sta} and f_{sti} and analyzed again via repeated ANOVA measures with the Bonferroni post hoc tests. Consequently, we observed the main effects of f_{sta} ($F_{4,28} = 20.9$, $p < 0.001$) and f_{sti} ($F_{3,21} = 3.50$, $p < 0.05$). We observed significant interaction between S and f_{sta} ($F_{24,168} = 4.45$, $p < 0.001$), between S and f_{sti} ($F_{18,126} = 4.16$, $p < 0.001$), and between f_{sta} and f_{sti} ($F_{12,84} = 2.11$, $p < 0.05$).

The results of the analysis indicate that S_1 has significant differences between *no* f_{sta} *stimulus* and $f_{sta} = 5$, 20, 80 Hz ($p < 0.05$ at least for all f_{sta} pairs), S_2 has significant differences between *no* f_{sta} *stimulus* and $f_{sta} = 5$, 20, 80 Hz, $f_{sta} = 80$ Hz and $f_{sta} = 320$ Hz ($p < 0.05$ at least for all f_{sta} pairs). As described in related works [7], it is known that the intensity of perceived smoothness increases with higher frequencies. Thus, we conclude that S_1 and S_2 have no significant differences between *no* f_{sta} *stimulus* and $f_{sta} = 320$ Hz. The trend is also confirmed by the experimental results.

We should pay attention to the fact that, despite the application of electrical stimulation, S_1 and S_2 decreased as f_{sta} increased. Consequently, electrostatic force possesses more influence on hybrid tactile sensation when the same voltage is applied to both tactile displays. However, as shown in the Figure 7-S_2, part of the variance of frictional sensation decreased sharply ($f_{sta} = 20$ Hz and $f_{sti} = 640$ Hz, $f_{sta} = 80$ Hz and $f_{sti} = 10$ Hz, and $f_{sta} = 80$ Hz and $f_{sti} = 80$ Hz). Thus, the combination of electrical stimulus and electrostatic force possesses the potential to realize more realistic tactile sensation-rendering with the combination of frequency stimuli.

Bumpy (S3) and Touch (S4) Sensation

As shown in Figure 8, when we did not apply both stimuli, participants felt “flat” and “light touch” sensations (S_3 and S_4 were mapped at the left side on the graph). Next, S_3 and S_4 increased as f_{sti} increased. S_4 also increased as f_{sta} increased. When only f_{sti} stimulus was applied, S_4 was mapped in the range from “light touch” sensation to “neutral.” When only f_{sta} stimulus was applied, S_3 and S_4 were mapped in the range from “neutral” to “bumpy/touch” sensations.

As shown in Figure 8, a similar tendency is confirmed on “bumpy” sensations (S_3), compared to related work. Alternatively, touch sensations (S_4) increased as the frequency increased under the f_{sta}-only and f_{sti}-only conditions.

The results of the analysis indicate that S_3 has significant differences between $f_{sta} = 20$ Hz and $f_{sta} = 320$ Hz ($p < 0.05$ at least); and S_4 has significant differences between *no* f_{sta} *stimulus* and $f_{sta} = 5$, 20, 80 Hz ($p < 0.05$ at least for all f_{sta} pairs), between $f_{sti} = 10$ Hz and $f_{sti} = 640$ Hz, $f_{sti} = 80$ Hz and $f_{sti} = 640$ Hz ($p < 0.05$ at least for all f_{sti} pairs).

As with S_1 and S_2, we conclude that S_4 possesses no significant difference between *no* f_{sta} *stimulus* and $f_{sta} = 320$ Hz. However, we conclude that S_4 possesses a significant difference between high f_{sti} and low f_{sti}. We confirmed that this tendency differs from S_1 and S_2. Thus, S_4 is not affected by

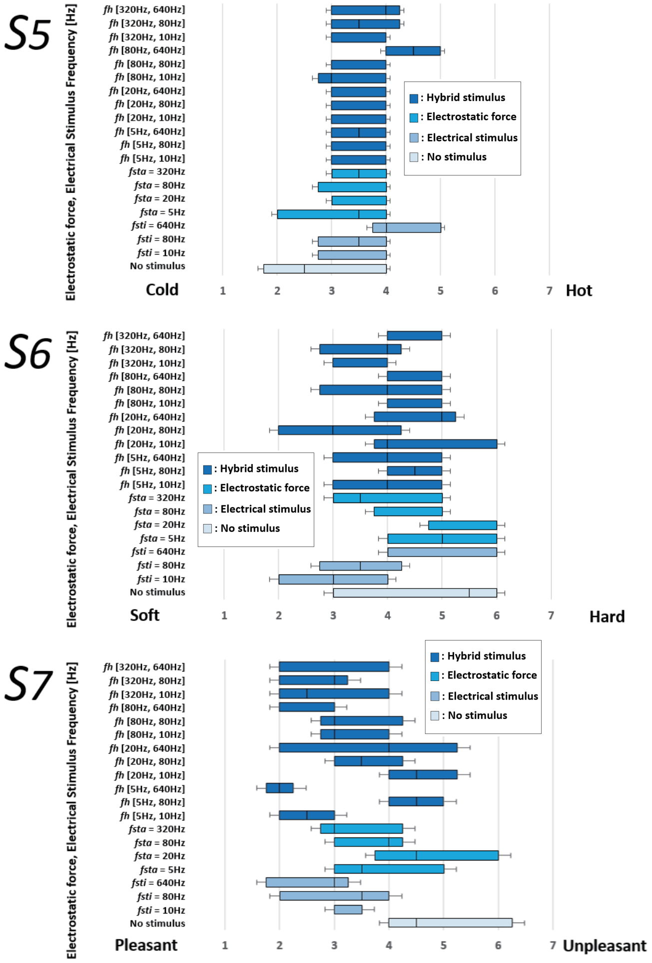


Figure 9. Result of the sensational evaluation of S_5, S_6 and S_7.

electrostatic force, and can be stably provided by applying f_{sti}.

Temperature (S5), Hardness (S6), Pleasant (S7) Sensation

S_5 was perceived as a little colder than neutral (Figure 9-S_5). We conclude that the results depend on the temperature of the sheet the user touches, or the grounded conductor which sits under the sheet, because the setup was almost unchanged from *no f_{sta} and f_{sti} stimulus*.

S_6 was mapped relatively as "neutral." However, when f_{sti}-only was applied, S_6 increased as f_{sti} increased. Additionally, S_6 decreased as f_{sta} increased (Figure 9-S_6). In the case of hybrid stimulus, S_6 was also mapped relatively "neutral," although the variance was higher.

Analysis results of S_7 show significant difference between *no f_{sti} stimulus* and f_{sti} = 640 Hz. We assume that the frequent stimulus to nerves caused an unpleasant sensation, such as pain. In consideration of the safety of the subjects, we presented f_{sta}-only and f_{sti}-only before the actual experiment, and confirmed that the subjects did not perceive pain with the stimuli. However, the increase in f_{sti} was still perceived as unpleasant.

Perceived Sensation

Some participants answered with words like "smooth surface" at *no f_{sti} stimulus* and f_{sti} = 10 Hz (e.g., metal plate or paper) without electrostatic force and f_{sta} = 320 Hz without electrical stimulus. Additionally, the roughness of the answered words increased as f_{sti} increased. Some participants perceived a "rough surface" such as sandpaper or cloth at high f_{sti}. These answers nearly agree with the analysis. When electrical stimulus was added to electrostatic force with high frequency, the answers changed to "roughness surface" and some participants said it was like a "rough paper" or "stone surface." These answers nearly agree with those when only electrical stimulus was applied.

Summary of user study

We conducted evaluations of the characteristics of tactile sensation while applying electrical stimulus and electrostatic force. Our evaluations showed that tactile sensation is influenced by the interaction between electrical stimulus and electrostatic force with various frequency conditions.

According to the results based on the participants' answers in their own words, there are no significant changes of the perceived sensations when applying both stimuli. Electrostatic force possesses more influence on hybrid tactile sensation when the same voltage is applied to both tactile displays with S_1, S_2 and S_3. Only S_4 is not affected by electrostatic force, and can be stably provided by applying f_{sti}. S_5, S_6 and S_7 are not affected by the combination of both stimuli.

Finally, the combination of electrical stimulus and electrostatic force possesses the potential to realize more realistic tactile sensation-rendering with the combination of frequency stimuli with S_2. We believe that knowledge of the effects of applying hybrid stimuli will contribute to the evolution of tactile display and is relevant to future work on haptic feedback applications.

APPLICATION

In this section, we show applications of the proposed method.

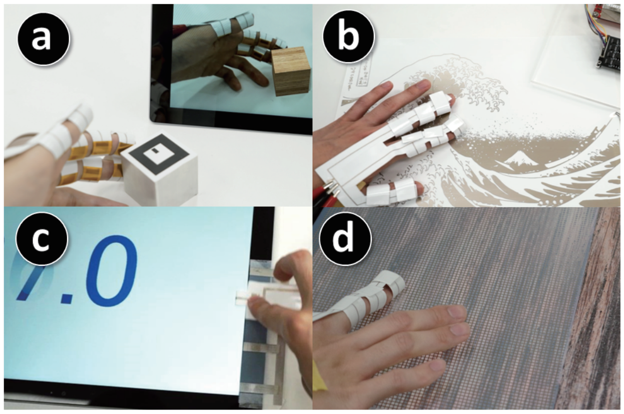


Figure 10. Proposed applications.

Wearable Tactile Display

We prototyped a virtual reality (VR) glove for multi-finger stimulation using the proposed method, shown in Figure 10-

a. The electrode patterns are printed on paper or PET film and the VR glove is highly flexible. The VR glove is easily designed and fabricated, because the design is easily changed with illustration software. Our prototyped VR glove alters the surface of grounded conductive objects using a combination of electrical stimulus and electrostatic force. We developed a simple application which adds a wooden surface on a rolled paper object. The appearance of the objects is also altered with augmented reality. The users can experience simulated altered wooden surfaces on grounded conductive objects both tactilely and visually. The electrostatic force stimulation requires a grounded flat surface. The grounded conductive surface can be also printed with conductive ink. With these methods, tactile sensation can be easily added to printed pictures and photographs. Figure 10-b shows an example of tactile augmentation to a printed photograph. This method can also be applied to picture books, paper craft, and origami.

Interface Applications

Our proposed method can fabricate tactile displays with optional shapes because of the flexibility of the substrate, which enables the tactile displays to be cut and placed onto curved surfaces. Figure 10-c shows the application of a slider-type interface. A sheet with comb-like electrode for electrostatic force is put at the edge of a tablet device. When a user moves a slider on the sheet, a touch point printed on the slider moves with it. Consequently, scroll-input is provided to the touchscreen. Our proposed system can add tactile feedback spatially, such as with snap, because frictional force modulated by electrostatic force is applied only to the electrode. Additionally, the slider can be smoothly moved under low-peak voltage conditions. We developed a system that can change the input through the slider continuously or discretely. When tactile feedback is added with high peak voltage, the value displayed on the screen changes discretely. With low-peak voltage, the slider can be moved smoothly and the value continuously changes.

Figure 10-d shows a system resembling TeslaTouch [7] using the proposed method. A grid electrode pattern is printed on transparent film. The film is put onto a commercial desktop monitor. Hand position is measured with a video camera. Tactile feedback is changed with the movement of the hand and predictably affects contents displayed on the monitor.

LIMITATION

In this study, we focused on electrical stimulus and electrostatic force with the tactile presentation method. The electrostatic force can be applied only to flat conductive surfaces because rough surfaces jam the electrostatic force. However, the proposed method possesses potential for tactile sensation printing. The proposed method is effective especially for content that requires thin flexible materials. For example, tactile sensation can be easily added to books, as shown earlier. Electrostatic force stimulus is a passive method, because subjects need to move their finger to perceive a sensation. Therefore, the electrical stimulus is not suitable for objects held still. The proposed system could apply a maximum of 0.6 mA and 600 V. Sometimes, users felt discomfort under high voltage conditions. Additionally, perceived tactile sensations might be different for each subject. In future work, we plan to investigate optimal peak voltages of each voltage condition. We also plan to develop a system that can estimate optimal voltage conditions, if needed.

We experimentally confirmed that the durability of the tactile display can be improved by several coating methods. However, other contributors to damage, such as bending and degradation with time, were not considered. When more durable devices are required, it is better to fabricate the devices with printed boards and ITO. The advantages of the proposed method are low cost and fast fabrication. The proposed tactile display can be easily designed with illustration software and quickly printed with an inkjet printer. The total cost is a few cents per sheet. The advantages are effective for trial-and-error prototyping. Thus, frequent replacement of the sheet is not an issue in the short-term usage scenario inherent to the trial and error process of prototyping and design of tactile displays. For now, we do not assume a long-term use for the proposed tactile display. In addition, we think the replacement of the sheet for each user has an advantage of hygiene perspective.

In the EVALUATION section, we conducted experiments only applied the tactile display to a single finger. However, mechanoreceptors are most dense in the fingertip. Thus, the density of the mechanoreceptors results in a high degree of sensitivity to tactile stimuli in the fingertip, which was sufficient for our experiments. We suggest that a similar trend would be observed in the large area stimulation of hand.

CONCLUSION

In this paper, we proposed a hybrid tactile display which can provide “electrical stimulus” and “electrostatic force.” We also proposed prototyping technique that fabricating the hybrid tactile display using a double-sided inkjet printing. Our prototyping technique enable easy and inexpensive fabrication of the experimental device and facilitates future work in the haptics field.

We evaluated the user experience of the tactile sensations using combinations of electrical stimulus and electrostatic force. According to the results, tactile sensation is influenced by the interaction between electrical stimulus and electrostatic force with various frequency conditions. The proposed hybrid tactile display using an electrical stimulus and an electrostatic force presents a more realistic tactile presentation that has richer information than tactile feedback with a simple stimulus. Finally, we showed a variety of novel applications for our conductive inkjet printing technique. A part of this study was presented in ACM UIST’17 demo [19].

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