

Effect of Electrical Stimulation Haptic Feedback on Perceptions of Softness-Hardness and Stickiness While Touching a Virtual Object

Vibol Yem*, Kevin Vu**, Yuki Kon*, and Hiroyuki Kajimoto*

*The University of Electro-Communications, Tokyo, Japan. **Polytech Paris UPMC, Paris, France

ABSTRACT

With the advantages of small size and light weight, electrical stimulation devices have been investigated for providing haptic feedback in relation to virtual objects. Electrical stimulation devices can directly activate sensory receptors to produce a reaction force or touch sensations. In the current study, we tested a new method of electrically inducing force sensation in the fingertip, presenting haptic feedback designed to alter perceptions of softness, hardness and stickiness. We developed a 3D virtual reality system combined with finger-motion capture and electrical stimulation devices. We conducted two experiments to evaluate our electrical stimulation method and analyzed the effects of electrical stimulation on perception. The first experiment confirmed that participants could distinguish between the directions of the illusory force sensation, reporting whether the stimulation flexed their index finger forward or extended it backward. The second experiment examined the effects of the electric current itself on the intensity of their perception of the softness, hardness and stickiness of a virtual object.

Keywords: Softness-hardness perception, stickiness perception, electrical stimulation, virtual touch.

Index Terms: H.5.2 [Information Interfaces and Presentation]: User Interfaces—Haptic I/O

1 INTRODUCTION

Technological progress in computer graphics and head-mounted displays has enabled increasingly high-quality visual interaction with the virtual environment. Fully immersive virtual reality requires a high-quality tactile device to reproduce sensations such as softness-hardness and stickiness. To be used in free-space virtual environments, devices must also be wearable.

Many wearable tactile devices for virtual reality have been proposed [16][18][19], but most are vibrotactile systems, which are limited in terms of the object properties they can represent. For example, softness, hardness and stickiness, which are all important material properties that can be fully presented with conventional ground-fixed haptic displays [12][21][17], cannot be presented by currently available wearable vibrotactile devices. To present the sensation of softness-hardness or stickiness of a virtual object to the fingertips, in addition to the sensation of a contact area [27][4], it also requires a force sensation on the skin of the fingertips to induce a sensation of forward-flexion or backward-extension. Several previous studies have used asymmetric vibration to produce illusory force sensations in the finger [30][2]. However, use of a mechanical actuator increases the size of the device.

Systems that use electrical stimulation have been extensively studied in efforts to produce a small device with high responsiveness and energy efficiency. This method uses an electric current to directly activate sensory receptors in the finger. Most previous studies of electrical stimulation have presented tactile sensations to the palm [8], or force feedback to the forearm, elbow or wrist [13][9][5][25][14]. However, these previous studies have not presented a force sensation to the finger, which is important for haptic feedback of an operation using the fingertips. Moreover, they have not investigated the effects of this stimulation method on the perception of softness-hardness and stickiness while presenting haptic feedback of virtual touch.

In the current study, we tested a system that uses electrical stimulation as haptic feedback to induce the sensations of the softness-hardness and stickiness of a virtual object in the fingertip. As Fig. 1 shows, the electrode array for stimulation mounted on the fingertip was dense, small, and lightweight. We proposed a method of generating an illusory sensation of a force flexing the fingertip forward or extending it backward. Here we examine the use of electrical stimulation to present these types of force sensations, and the effects of the electric current itself on the perceived intensity of softness, hardness and stickiness while touching a virtual object.

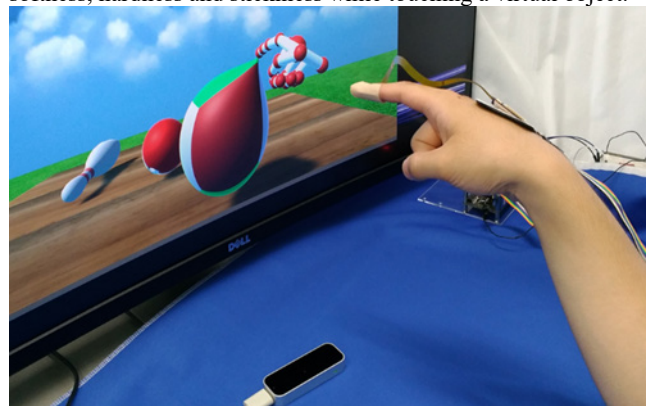


Figure 1: A 3D virtual reality system using electrical stimulation to present force feedback sensations of softness-hardness and stickiness to the index finger while pressing or releasing a virtual ball

2 RELATED WORK

2.1 Haptic Feedback on the Fingertip for Virtual Reality Interaction

Haptic technologies have traditionally used grounded actuators to produce force feedback in virtual environments [12][21][17]. Outputting a force through an end effector driven by an actuator enables the user to perceive the stiffness of a virtual object, from very soft to hard. However, such a device requires a large space, and stimulation involves a tool-based interaction that limits the movement of the user's fingers. Other devices deliver kinesthetic sensations using a wearable robotic mechanism [15][1]. These are typically exoskeleton devices that can deliver grasping force

* {yem, kon, kajimoto}@kaji-lab.jp

**kevin.vu@hotmail.fr

feedback to the fingertips, without workspace limitations. Other devices provide force feedback to the finger pads by presenting a pressure or skin deformation sensation [11][26]. These cutaneous stimulation devices are mainly used for touch or surface exploration interactions in the virtual environment. However, because all the above wearable devices use mechanical actuators to generate a physical force for the haptic sensation, they are still limited by their large size and low responsiveness. In addition, previous studies have not confirmed that these devices can present force feedback that induces the sensation of stickiness.

Several other studies have focused on the illusion that is induced by changing the contact area, reporting that changing the contact area of the force applied to the skin affects the sensation of an object's softness and stickiness [27][4]. In contrast, the current study focused on the illusory force sensation produced by electrical stimulation delivering haptic feedback to the fingertip. We studied the effects of the electric current itself on the perception of softness-hardness and stickiness while touching the virtual object.

2.2 Sensory Receptors and Electrical Stimulation

Haptic (force) perception is thought to rely on the activities of proprioceptive sensory receptors that exist inside muscles (muscle spindles) and tendons (Golgi tendon organs). The muscle spindles are sensitive to muscle contractions, and receive information about the distance and rate of stretch within the muscle. The Golgi tendon organs are receptors that activated by active contraction of a muscle, and receive the information about muscle tension. On the other hand, tactile perception is thought to rely on the activities of mechanoreceptors inside the skin [6]. They are Merkel cells for pressure, Meissner's corpuscles for low frequency vibration, Pacinian corpuscles for high-frequency vibration, and Ruffini endings for skin shear deformation. Vibration is mainly used to present the sensation of material roughness, whereas pressure and skin shear deformation are used to induce the sensation of a reaction force while grasping or rubbing an object.

Several studies have attempted to reproduce haptic or tactile feedback using electrical stimulation to directly activate these receptor nerves. Based on previous reports, in the current study we classified electrical stimulation into three methods. The first method employs electrical muscle stimulation (EMS) to stimulate the muscles, thereby generating a sensation of force, and to control of the angle of the joint. Widely used in human interface development [13][25][14], in the field of rehabilitation this method is known as functional electrical stimulation (FES).

The second method is tendon electrical stimulation, which directly stimulates the force receptors related to haptic sensation. This method is designed to control the human subjects' ability to perceive an illusory sensation of an external force and joint motion. Kajimoto [9] and Gandevia [5] reported that electrical stimulation can be used to induce illusory motion of the hand.

The third method is electrotactile stimulation, of which there are two types: anodic and cathodic stimulus presentation. Anodic stimulation occurs when the stimulus electrode is connected to a high potential and the other electrodes are connected to a low potential. In contrast, the stimulation becomes cathodic when the stimulus electrode is connected to a low potential and the other electrodes are connected to a high potential. Kajimoto et al. [7] reported that sensations of pressure and low-frequency vibration can be simulated by changing the polarity of the current, by considering the activating function [23][22]. Our previous study proposed the use of both electrotactile stimulation and mechanical stimulation to selectively activate all four types of mechanoreceptors [28]. We found that the pressure-like sensation induced by cathodic stimulation affected the sensation of softness-hardness, whereas the low frequency vibration-like sensation induced by anodic stimulation affected the sensation of roughness.

Takei et al. [24] used anodic stimulation to increase the illusory sensation of the softness of a material by changing the stimulation area. Their method was based on the notion that an illusory sensation of softness can be induced by changing the contact area. However, they did not study the effects of the electric current itself on the perception of softness.

Although electrical stimulation has been widely studied and used to present haptic feedback in a VR environment, the effect of the electric current itself on material perception while touching a virtual object has not been confirmed. Moreover, reproducing an illusory sensation of a force moving the fingertip still presents a challenge.

3 SYSTEM

Fig. 1 shows the system used in our study, consisting of an electrical stimulation device to present haptic feedback to the fingertip, a virtual environment to provide visual feedback, and a motion capture device (Leapmotion Inc.) to measure finger movement.

3.1 Electrical Stimulation Device

We used the same electrical stimulation kit used in [8] to control the intensity of the electric current. The microcontroller (Mbed LPC 1768, NXP Co., Ltd.) and a computer can transmit the data to each other by serial communication. The intensity of the electric current can be adjusted within the range 0 mA to 5 mA from the keyboard of the computer.

The two types of electrodes shown in Fig. 2 were employed. The first was an electrode array placed on the fingertip. All the electrodes were connected to the pins of a high voltage shift register (HV507, Supertex Inc.), which enabled the electrode being stimulated to be selected. The second was a large electrode (50 mm × 50 mm, NPP 40222, BODYMED) placed on the back of the hand. A switch (MOSFET 2SK1313, Renesas Electronics) was used to connect this electrode either to ground or to a high impedance.

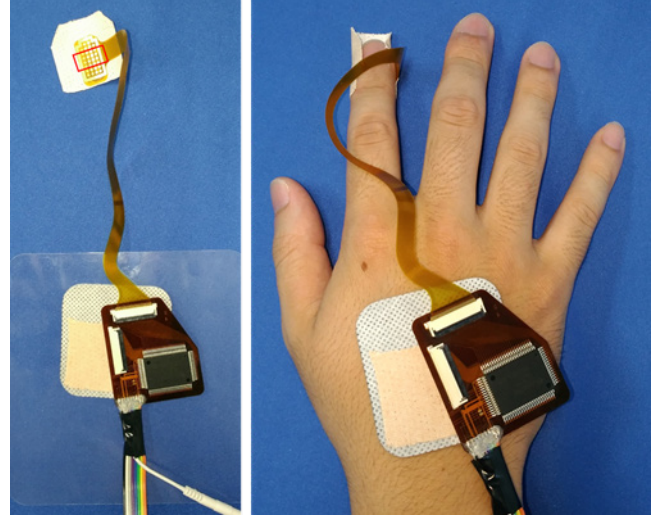


Figure 2: Electrodes used for electrical stimulation (left) and the electrical stimulation device shown attached to the hand. The electrodes enclosed in the red box are the cathodic electrotactile stimulation points.

3.2 Electrical Stimulation Algorithm

We used an electric current with the pulsed waveform shown in Fig. 3 to stimulate the sensory nerves and produce haptic feedback on the fingertip of the index finger. The electric current had a pulse width of 100 μ s, with two pulses per burst at intervals of 5 ms. The refresh frequency was varied between 20 and 50 Hz, and the pulse height was adjusted from 0 to 5 mA.

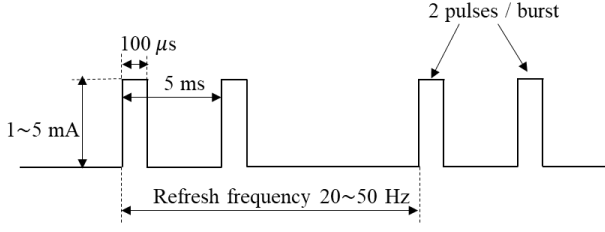


Figure 3: Pulsed waveform of the electrical stimulation

Our study was designed to provide a sensation of force to the fingertip without controlling the movement of the finger joints. Users could therefore move their finger freely while receiving haptic feedback on the fingertip. To achieve this, we decided to stimulate the sensory nerves to the tendons inside the finger by causing an electric current to flow from the fingertip to the back of the hand. As Fig. 4 (top) shows, we connected all the electrodes at the fingertip to a high voltage and the electrode on the back of the hand to ground. This method avoided muscle spindle stimulation because the muscles that control the finger joints are inside the palm and forearm [20]. We designed the total area of the electrodes at the fingertip to be smaller than the area of the electrode on the back of the hand to converge the electric current distribution and allow a higher intensity at the fingertip. This method mainly activates the sensory nerves of mechanoreceptors and flexor tendons that are near the fingertip. We tested this method and confirmed that it produced the sensation of an illusory force flexing the fingertip forward, and we applied it to induce the sensation of stickiness.

Since it is difficult to activate mainly the extensor tendons through electrodes placed at the fingertip, we used cathodic electrostatic stimulation to present an illusory sensation of a force extending the fingertip backwards. As Fig. 4 (bottom) shows, the electrode at the stimulation point was connected to ground, while the others were connected to a high voltage. This stimulation method has been previously used to activate mainly Merkel cells that respond to pressure on the fingertip [7][29].

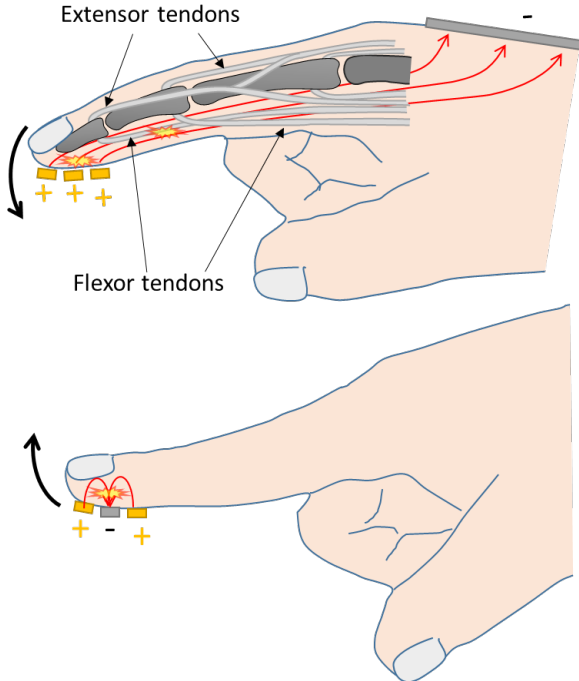


Figure 4: Electrical stimulation of tendons (top) and cathodic electrostatic stimulation (bottom) designed to present an illusory sensation of a force flexing the finger forward and backward

3.3 Visual Feedback and the Force Feedback Algorithm

The movement of a virtual finger in a virtual environment should follow the position of the finger in the real world, as measured with a motion capture device. However, a common issue is that the virtual finger can easily move inside the virtual rigid body when the user attempts to touch or press it because there is no physical force to resist the finger (Fig. 5 [left]). In the current study, we sought to address this issue. To achieve this, we made the virtual finger invisible when it moved inside the virtual rigid body, and showed a copy of the finger moving on the surface of the object (Fig. 5 [right]).

The following equation is used to determine the strength of the force feedback on the fingertip with the intensity of the electric current.

$$i = (1 + k_i \Delta x) i_{th} \quad (1)$$

where i is the intensity of the electric current (i.e., pulse height) applied to the finger, k_i is a constant and i_{th} is the sensation threshold of the electric current. Δx is the distance the finger moves inside the object when pressing it or the distance the finger is from the object when releasing with stickiness (Fig. 6).

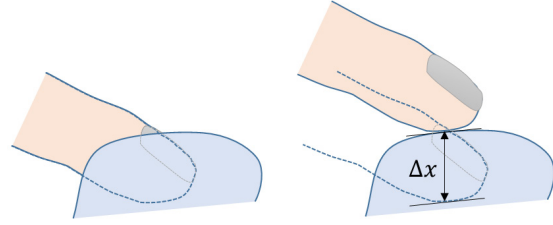


Figure 5: Representation of a common issue in which the virtual finger moves inside the virtual rigid body (left), and the proposed algorithm for maintaining finger contact with the surface of the virtual object

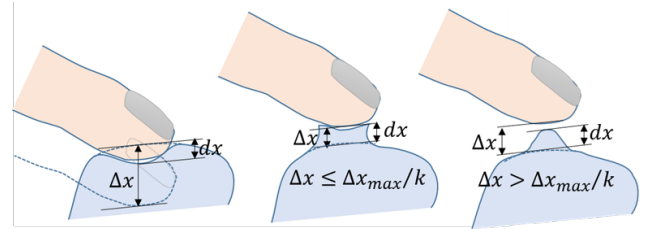


Figure 6: Deformation of a virtual object when pressing with a finger (left), releasing with stickiness (middle) or after releasing (right).

The surface of the virtual object starts to deform when the finger applies a force to the object, or releases from the object with stickiness. The amount of deformation of a contact point between the fingertip and a virtual surface can be expressed by the following equation.

$$dx = \begin{cases} \frac{\Delta x}{k} & \text{(for pressing)} \\ \Delta x & \text{(for releasing with stickiness)} \\ \frac{\Delta x_{max}}{k} e^{-c \times t} \cos(\omega t) & \text{(after releasing)} \end{cases} \quad (2)$$

where dx is a deformation distance of a contact point, k and c represent the spring and damping coefficients of the virtual object, and t is time. Δx_{max} is a constant that limits the amount of

deformation when releasing (Fig. 6 [right]). ω is the frequency of virtual surface vibration. After the finger releases from the surface ($\Delta x > \Delta x_{max}/k$), as t starts to increase from zero, the contact point starts to vibrate. We used wave equation to calculate other vertices that surround the contact point. Fig. 7 shows the deformation of a virtual ball.

With the above algorithm, the force feedback and visual feedback can be controlled independently by changing the values of k_i , k and c .

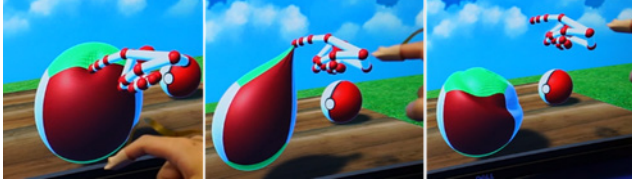


Figure 7: Visual interaction with object deformation while pressing (left), releasing with stickiness (middle), and surface vibration after releasing (right).

4 EXPERIMENT 1: DISCRIMINATING DIRECTION OF ILLUSORY FORCE ON THE FINGERTIP

In this experiment, we selectively presented cathodic electroactile stimulation and electrical stimulation of the tendons. Cathodic electroactile stimulation elicits the sensation of an illusory force that extends the fingertip backward, whereas electrical stimulation of the tendons elicits the sensation of an illusory force flexing the fingertip forward. This experiment was conducted to investigate whether participants could distinguish between the directions of these two illusory force sensations while presented with electrical pulses of different refresh frequencies.

4.1 Design

Four refresh frequencies (20, 30, 40, 50 Hz) and two directions for the force sensation (backward-extension and forward-flexion) were set as the conditions. We recorded the number of correct responses in distinguishing the direction of the force (correct response rate) and the reaction time (i.e., the total time from presentation of the stimulus until the participant responded by moving the mouse and clicking the answer button) for each of the frequencies. Trials were repeated four times for each condition, resulting in a total of 32 trials (4 frequencies \times 2 directions \times 4 trials) for each participant. Each condition was randomly presented. The stimulus was presented continuously until participants responded.

4.2 Participants and Procedure

Ten participants took part in this experiment (eight males and two females, aged between 21 and 33 years old). One participant was left-handed, while all the others were right-handed.

Fig. 8 shows an overview of Experiment 1. Participants were asked to clean their fingertip with alcohol before the experiment. Participants sat on a chair, and we attached the electrodes to the index fingertip and the back of the right hand. Each participant was instructed to place their right hand on the desk with the palm down, as shown in Fig. 8. Before each trial, participants adjusted the volumes of both electrical stimulation modes until they could clearly perceive the direction of the force. In each trial, participants used their left hand to move the mouse and click the middle button displayed on the computer's monitor to start the stimulus. After they identified the direction as backward-extension or forward-flexion, they moved the mouse and clicked either the upper or lower button as appropriate. Because we want to compare the reaction time for each condition, we asked participants to report the direction as quickly as possible after clicking the stimulus button.

4.3 Results for Experiment 1

Fig. 9 and 10 show comparisons of the mean values of the response rates and reaction times between the two modes of stimulation for each frequency condition. Error bars represent standard deviation.

A 4 (frequency) \times 2 (direction) two-way repeated measures analysis of variance (ANOVA) was conducted to analyze the correct response rate and reaction time. No significant effects of frequency or direction, or any interaction between frequency and direction were observed for either correct response rate or reaction time.



Figure 8: Setup for Experiment 1. Participants used their left hand to click one of three buttons displayed on the monitor to start the stimulus or report the perceived direction.

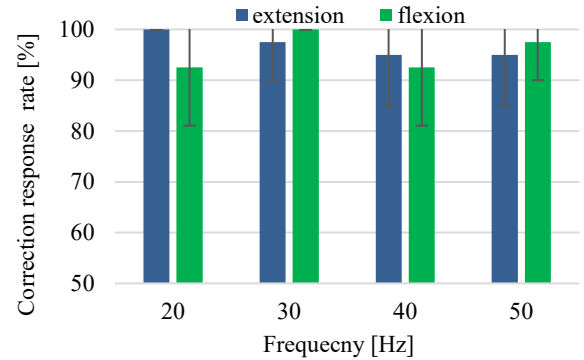


Figure 9: Comparison of the mean correct response rates for extension and flexion at each frequency

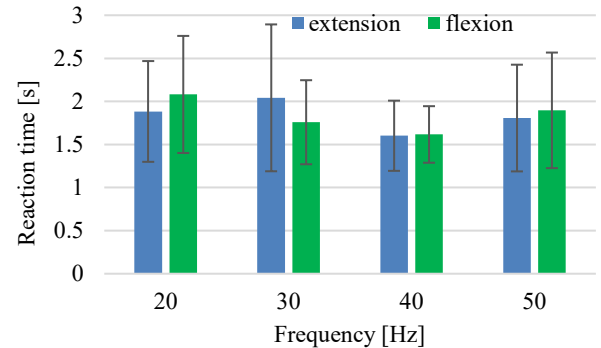


Figure 10: Comparison of the mean reaction times for extension and flexion at each frequency

The results revealed that the mean correct response rate was over 90 %, regardless of the refresh frequency or the perceived direction of the force-like sensation. Before and after the experiment we asked all participants to confirm whether they could clearly perceive and distinguish the direction of the force. Participants

responded that they could perceive the direction clearly for most trials. From this, we concluded that our system could effectively produce the sensation of an illusory force for both backward-extension and forward-flexion. By selectively presenting these two sensations, we were able to present haptic feedback corresponding to pressing or releasing a virtual object. The mean reaction time ranged from 1.5 to 2 s. There was a delay in the response times because participants needed to move the mouse to click either the upper or lower button after they had perceived the direction.

5 EXPERIMENT 2: EFFECT OF ELECTRIC CURRENT ON PERCEPTIONS OF SOFTNESS-HARDNESS AND STICKINESS

This study was designed to investigate how electric current affects participants' material perception. The results of Experiment 1 indicated that our electrical stimulation system was effective in presenting an illusory force sensation in two modes: extending the fingertip backward and flexing it forward. In Experiment 2, we selectively induced these illusory force sensations using visual feedback to represent the softness-hardness and stickiness of a ball in the virtual world. When the participant performed a pressing action, the system presented cathodic electrostatic stimulation with reaction force feedback to induce the perception of the object pushing on their fingertip. In contrast, when a releasing action was performed, the system presented electrical stimulation of the tendons so that participants perceived a force flexing their fingertip forward.

The results of Experiment 1 revealed no significant differences between the mean correct response rates under all frequency conditions. However, because the highest mean response rate occurred when the frequency was 30 Hz, we chose this value for Experiment 2. The intensity of the electric current and the amount of deformation in the visual feedback were calculated using Equations (1) and (2). To avoid causing pain to participants, the maximum electric current i_{max} was limited to $1.4 \times i_{th}$ for pressing actions and $1.2 \times i_{th}$ for releasing actions. We chose a ball as the virtual object for visual feedback because the distance from any point on the surface to the center is the same, producing the same shape of deformation regardless of the contact position on the surface.

5.1 Design

We divided the evaluation into two types of virtual object interaction: pressing the surface (pressing) of the virtual object and releasing from the surface with stickiness (releasing). Each action was evaluated separately. In evaluating pressing, there was no haptic or visual feedback when participants released from the surface, but both haptic and visual feedback were included for releasing. Participants were asked to evaluate softness-hardness for both actions, and to evaluate stickiness only for releasing. The sensations were evaluated using a nine-step Likert scale, where 1 represents no perception at all and 9 represents very soft, very hard or very sticky. In many evaluation methods, softness and hardness are included on the same axis (e.g., -3: very soft, 0: in the middle, 3: very hard). However, in our evaluation we presented softness and hardness on two independent axes, allowing participants to report when they perceived neither softness nor hardness.

Fig. 11 and 12 show the three conditions for visual feedback presented by changing the spring and damping coefficients of the object ($\{k, c\}$, $\{2k, 3c\}$, $\{3k, 9c\}$), and the three conditions for electrical stimulation presented by increasing the rate coefficient of the electric current ($(k_i, 2k_i, 3k_i)$ for pressing; $(0.5k_i, k_i, 1.5k_i)$ for releasing). The experiment was conducted once for each condition, resulting in a total of 18 trials (3 visual feedback \times 3 electrical stimulation \times 2 processes) for each participant. Conditions were presented in a random order.

5.2 Participants and Procedure

Eight participants took part in this experiment: six males and two females, ranging in age from 21 to 24 years. All participants were right-handed.

As in Experiment 1, participants were asked to clean their fingertip with alcohol before the experiment, and sit on a chair. We attached electrodes to the index fingertip and to the back of the right hand. As Fig. 1 shows, the participant placed their elbow on the desk to keep their hand movements stable. We explained how to move the hand and index finger at the same speed, over the same distance and to the same contact point on the surface in every trial. Participants adjusted the volumes of both electrical stimulation modes until they began to feel the electrical stimulation; this was taken as the sensation threshold i_{th} for both modes. Participants performed several training sessions, then experienced all the experimental conditions with visual and electrical force feedback. They were asked to remember the intensities of softness, hardness and stickiness during the releasing action. After participants experienced these conditions, we presented each trial in random order again, and asked them to respond with intensity scores for softness-hardness and stickiness from 1 to 9.

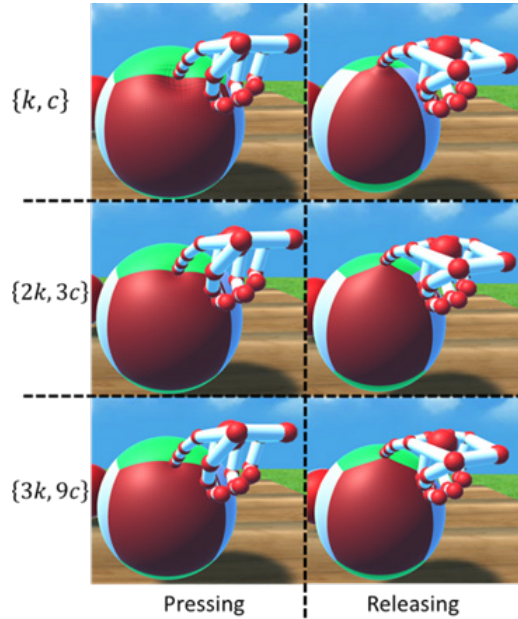


Figure 11: Visual feedback for all spring-damping conditions while pressing or releasing

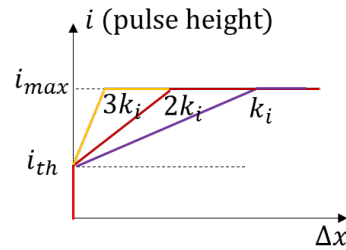


Figure 12: Electric current (pulse height) for presenting illusory force feedback when pressing and releasing

5.3 Results for Experiment 2

Fig. 13 shows a comparison between the mean values of the softness-hardness intensity for the electrical stimulation conditions for each visual feedback condition when pressing. We separated

softness and hardness in the data analysis because they are two opposite perception types.

A 3 (electrical stimulation) \times 3 (visual feedback) two-way repeated measures ANOVA was conducted for the softness intensity analysis, and the results were validated by Mauchly's sphericity test. Significant effects were found for electrical stimulation ($F[2, 14] = 10.25, p < 0.01$), visual feedback ($F[2, 14] = 41.44, p < 0.001$) and the interaction between these two main factors ($F[4, 28] = 3.0, p < 0.05$). Bonferroni post-hoc tests indicated a significant difference ($p < 0.05$) in the visual feedback condition between electrical stimulations k_i and $3k_i$ for $\{k, c\}$. Significant differences were found between the separate visual feedback conditions ($p < 0.01$ for all), except between $\{2k, 3c\}$ and $\{3k, 9c\}$ for electrical stimulations k_i and $3k_i$. We conducted the same analysis for hardness intensity, and sphericity was also confirmed. The analysis revealed significant effects for electrical stimulation ($F[2, 14] = 0.72, p < 0.05$) and visual feedback ($F[2, 14] = 19.25, p < 0.001$), but no significant interaction was found between these main factors. Pairwise comparison using the Bonferroni test revealed a significant difference between the separate visual feedback conditions ($p < 0.05$ for all).

Fig. 14 shows the relationship between softness and hardness for the pressing action. A correlation analysis resulted in standard values of R for electric current conditions $k_i, 2k_i$ and $3k_i$ of 0.60, 0.78 and 0.79 respectively.

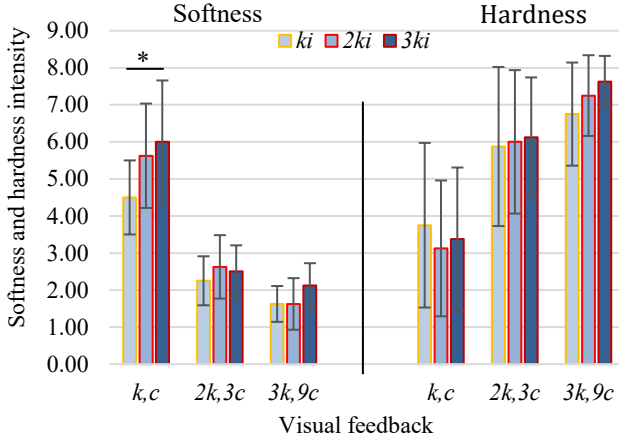


Figure 13: Comparison of analysis results for pressing: mean values of softness intensity (left), and mean values of hardness (right). An asterisk (*) indicates where $p < 0.05$.

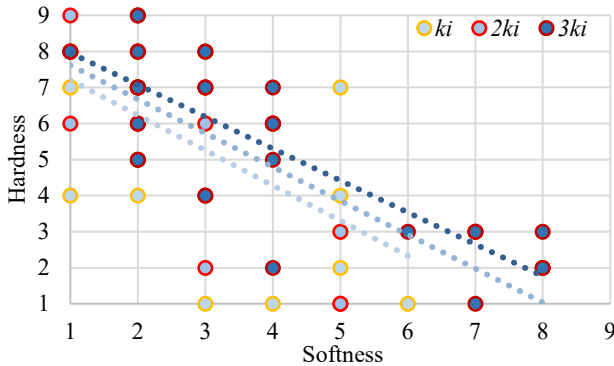


Figure 14: Relationship between softness and hardness for pressing

Fig. 15 shows a comparison between the mean values of the softness-hardness intensity for the electrical stimulation conditions

for each visual feedback condition when releasing. As in the analysis for pressing, we separated softness and hardness in the data analysis.

A 3 \times 3 two-way repeated measures ANOVA was again conducted for the softness intensity analysis and the results were validated by Mauchly's sphericity test. The analysis revealed no significant effects for electrical stimulation. However, a significant effect was found for visual feedback ($F[2, 14] = 39.03, p < 0.001$) and a significant interaction was found between these factors ($F[4, 28] = 2.70, p = 0.05$). Bonferroni post-hoc tests revealed a significant difference between k_i and $1.5k_i$ for $\{2k, 3c\}$ ($p < 0.05$). Differences approaching significance were found between $0.5k_i$ and k_i ($p = 0.08$), and between k_i and $1.5k_i$ ($p = 0.06$). Significant differences between the separate visual feedback conditions were found ($p < 0.05$ for all), except between $\{2k, 3c\}$ and $\{3k, 9c\}$ for electrical stimulations k_i and $2k_i$. The same analysis for hardness intensity also confirmed sphericity. No significant effects were found for electrical stimulation, nor any significant interaction. However, a significant effect was found for visual feedback ($F[2, 14] = 35.47, p < 0.001$). Pairwise comparison using the Bonferroni test indicated a significant difference in the visual feedback conditions between $\{k, c\}$ and $\{2k, 3c\}$, and $\{k, c\}$ and $\{3k, 9c\}$ ($p < 0.01$ for each).

Fig. 16 shows the relationship between softness and hardness for releasing. A correlation analysis resulted in standard values of R for electric current conditions $k_i, 2k_i$ and $3k_i$ of 0.62, 0.72 and 0.65 respectively.

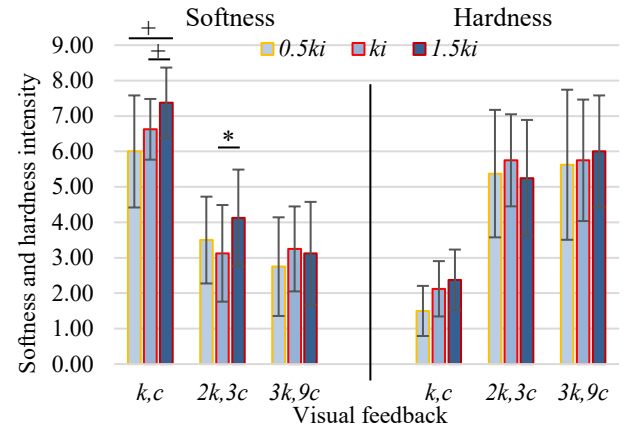


Figure 15: Comparison results for releasing: mean values of softness intensity (left), and mean values of hardness (right). A plus (+) and an asterisk (*) indicate where $p < 0.1$ and $p < 0.05$ respectively.

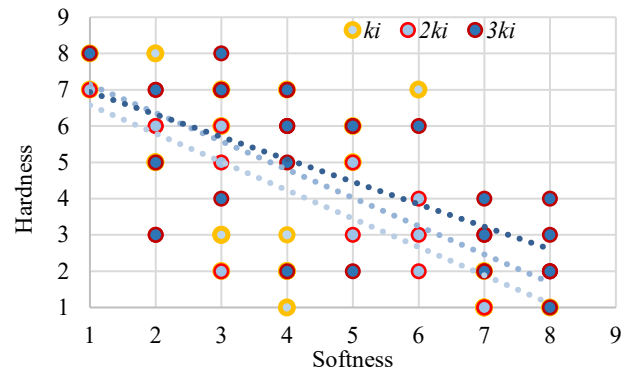


Figure 16: Relationship between softness and hardness for releasing

Fig. 17 shows a comparison between the mean values of the stickiness intensity when releasing for the electrical stimulation conditions for each visual feedback condition. A 3×3 two-way repeated measures ANOVA was conducted on the stickiness intensity and the results were validated with Mauchly's sphericity test. Significant effects were found for electrical stimulation ($F[2, 14] = 4.13$, $p < 0.05$) and visual feedback ($F[2, 14] = 27.15$, $p < 0.001$), but no significant interaction was found between these factors. Pairwise comparisons using the Bonferroni test indicated a significant difference between the visual feedback conditions $\{k, c\}$ and $\{2k, 3c\}$, and $\{k, c\}$ and $\{3k, 9c\}$ ($p < 0.01$ for each).

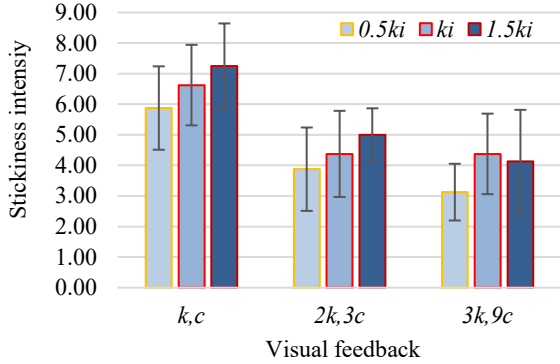


Figure 17: Comparison between the mean values of the stickiness intensity for the electrical stimulation levels for each visual feedback condition

6 DISCUSSION

6.1 Experiment 1

We used cathodic electrocutaneous stimulation and electrical stimulation of the tendons to induce an illusory sensation of force feedback in the fingertip. Our previous study found that cathodic electrocutaneous stimulation mainly activates Merkel cells, and elicits a pressure-like sensation in the fingertip [7] [29]. In the current study, we used this type of stimulation to present force feedback that flexed the fingertip backward. To the best of our knowledge, no previous study has reported a method that uses electrical stimulation to present force feedback that flexed the fingertip forward. Our proposed method presents this sensation by activating tendon sensory receptors inside the finger. We placed anodic electrodes on the fingertip and a ground electrode on the back of the hand to avoid stimulating the muscles that are inside the palm and forearm [20].

The results of Experiment 1 revealed that participants could distinguish between the two perceived directions of this force with high accuracy when the refresh frequency was between 20 and 50 Hz (Fig. 9). Before and after the experiment, we checked that participants could sense the direction of the force. All participants reported that they were able to perceive and easily distinguish the direction of the force in most trials, but it took time for them to concentrate when the direction was unclear. The reaction time results showed no significant difference between the directions at all refresh frequencies (Fig. 10). The mean reaction time was about 2 s because participants needed to move the mouse with their left hand to click the relevant button. These results revealed that our tendon stimulation method was effective in presenting force feedback to the fingertip.

6.2 Experiment 2

We used electrical stimulation as virtual touch feedback to induce an illusory force sensation that flexed the finger forward and

extended the finger backward. In some circumstances the perception by visual information is clearly effected by haptic information or vice versa when exploring the dimension or properties (e.g. stiffness) of the object. [10][3]. In this study, we used electrical stimulation to provide haptic information. Experiment 2 was conducted to investigate the effects of the electric current itself on the perception of softness-hardness and stickiness of an object while presenting visual feedback on the amount of deformation. We set the rate of increase of the electrical intensity (k_i in Equation (1)), which corresponds to the spring coefficient of the material, as the variable in the stimulation. When k_i became stronger, the displacement distance of the finger required for electric current i to reach i_{max} became shorter (Fig. 12).

The results revealed that the rate of increase of the electrical intensity affected the sensation of softness for both pressing and releasing (Figs. 13 and 15). When this intensity rate was increased, participants interpreted the material as being softer. However, this effect became gradually weaker when the visual feedback represented it as a harder material. This indicated that when participants interpreted the object as being soft through visual feedback, the intensity of their perception could be enhanced by increasing the electric current used for cathodic electrocutaneous stimulation and tendon stimulation.

In contrast, electrical stimulation was found to have a significant effect on the sensation of hardness for pressing, but not for releasing. This result indicated that the electric current used for cathodic stimulation to provide feedback while pressing was able to enhance the sensation of softness or hardness according to the participant's interpretation of the visual feedback. But no significant effect was observed for tendon stimulation when the participant interpreted the object as hard. Cathodic current mainly activates Merkel cells that respond to pressure sensations. To investigate whether this electrocutaneous stimulation provides a soft or hard perception of the material, we gave a demonstration at a local conference and asked participants for their comments. Most participants responded that the stimulation resulted in them perceiving the material as soft. In this experiment, the effect on the sensation of hardness was statistically weak compared with the effect on the sensation of softness. We therefore concluded that cathodic electrocutaneous stimulation alone affects the sensation of softness, and it only affects the sensation of hardness when visual feedback is provided.

We separated softness and hardness on two independent axes to allow participants to report if they perceived neither softness nor hardness. Although softness and hardness are often considered to be opposite, we instructed participants to evaluate the score on both axes, as shown in Figs. 14 and 16, because there is no clear boundary dividing softness and hardness. For example, hard material is softer than very hard material. In this case, participants reduced their score for hardness (e.g., from 8 to 7) and increased their score for softness (e.g., from 1 to 2).

We found that electrical stimulation had a significant effect on stickiness perception. As Fig. 17 shows, when the intensity of the electrical stimulation was increased, participants perceived the material as being stickier. The intensity of the stickiness perception decreased significantly when visual feedback indicated that it was a harder material. These results indicate that increasing the rate of the electric current pulse to stimulate the tendons in the finger affected the participants' perception of stickiness when they interpreted the virtual object as being made of a soft material.

In summary, the above results indicate that the electric current strongly enhanced participants' intensity of perception when they interpreted the object as being soft. However, the effect was reduced when they interpreted it as hard. In this experiment, we determined the deformation of the object over a large range so that participants were able to perceive sensations from very soft to very

hard. The information presented as visual feedback provided a larger range than when using electrical stimulation feedback.

7 CONCLUSION

In this study, we developed a virtual reality system that combined electrical stimulation and visual feedback to induce sensations of softness-hardness and stickiness of virtual objects in the index finger. We tested two modes of electrical stimulation. First, we induced a force sensation that flexed the finger forward. Second, we induced a pressure sensation that extended the fingertip backward.

In Experiment 1, we selectively presented these types of stimulation and asked participants to distinguish between them as quickly as possible. The mean response rate for distinguishing was over 90 % and mean reaction times were from 1.5 to 2 s, regardless of the refresh frequency of the electrical stimulation, which was varied from 20 to 50 Hz.

Experiment 2 was conducted to evaluate the effects of the electric current on the perception of softness-hardness and stickiness. The results revealed that the rate of increase of the electrical intensity affected the sensation of softness for both pressing and releasing, but affected the sensation of hardness only for pressing. In addition, the rate of increase of the electrical intensity also affected the intensity of stickiness.

ACKNOWLEDGMENTS

This work was partly supported by JSPS KAKENHI Grant Number JP17F17351, JP15H05923 (Grant-in-Aid for Scientific Research on Innovative Areas, "Innovative SHITSUKSAN Science and Technology"), and the JST-ACCEL Embodied Media Project.

REFERENCES

- [1] I. Choi, E.W. Hawkes, D.L. Christensen, C.J. Ploch, S. Follmer, "Wolverine: A wearable haptic interface for grasping in virtual reality." *Proc. IEEE/RSJ Intelligent Robots and Systems (IROS)*, pp. 986-993, 2016.
- [2] H. Culbertson, J.M. Walker, M. Raitor, A.M. Okamura, "WAVES: A Wearable Asymmetric Vibration Excitation System for Presenting Three-Dimensional Translation and Rotation Cues." *Proc. ACM Human Factors in Computing Systems (CHI)*, pp. 4972-4982, 2017.
- [3] M.O. Ernst, M.S. Banks, "Human integration visual and haptic information in a statistically optimal fashion." *Nature*, Vol. 415, No. 6870, pp. 429-433, 2002.
- [4] K. Fujita, H. Ohmori, "A New Softness Display Interface by Dynamic Fingertip Contact Area Control." *Proc. World Multiconference on Systemics, Cybernetics and Informatics*, pp. 78-82, 2001.
- [5] S.C. Gandevia, "Illusory movements produced by electrical stimulation of low-threshold muscle afferents from the hand," *J. Brain*, Vol. 108, No. 4, pp. 965-981, 1985.
- [6] L.A. Jones, S.J. Lederman, "Human Hand Function." 1st ed. USA: Oxford University Press, 2006.
- [7] H. Kajimoto, N. Kawakami, S. Tachi, "Electro-tactile display with tactile primary color approach." *Proc. Intell. Robots Syst.*, 2004.
- [8] H. Kajimoto, M. Suzuki, Y. Kanno, "HamsaTouch: Tactile vision substitution with smartphone and electro-tactile display." *ACM Human Factors in Computing Systems (CHI EA)*, pp. 1273-1278, 2014.
- [9] H. Kajimoto, "Illusion of Motion Induced by Tendon Electrical Stimulation." *Proc. World Haptic Conf. (WHC)*, pp. 555-558, 2013.
- [10] A. Lecuyer, S. Coquillart, A. Kheddar, P. Richard, P. Coiffet, "Pseudo-Haptic Feedback: Can Isometric Input Devices Simulate Force Feedback?" *Proc. IEEE Virtual Reality (VR)*, 2000.
- [11] D. Leonardis, M. Solazzi, I. Bortone, A. Frisoli, "A wearable fingertip haptic device with 3 DoF asymmetric 3-RSR kinematics." *Proc. IEEE World Haptics Conf.*, pp. 388-393, 2015.
- [12] J. Liu, A. Song, H. Zhang, "Research on Stiffness Display Perception of Virtual Soft Object." *Proc. IEEE Int. Conf. Information Acquisition (ICIA)*, pp. 558-562, 2007.
- [13] P. Lopes, S. You, L.P. Cheng, S. Marwecki, P. Baudisch, "Providing Haptics to Walls & Heavy Objects in Virtual Reality by Means of Electrical Muscle Stimulation." *Proc. Human Factors in Computing Systems (CHI)*, pp. 1471-1482, 2017.
- [14] P. Lopes, D. Yuksel, F. Guimbretiere, P.P. Baudisch, "Muscle-plotter: an Interactive System based on Electrical Muscle Stimulation that Produces Spatial Output." *Proc. User Interface Software and Technology (UIST)*, pp.207-217, 2016.
- [15] K.Z. Ma, P. Ben-Tzvi, "RML Glove - An Exoskeleton Glove Mechanism with Haptics Feedback." *IEEE/ASME Transactions on Mechatronic*, Vol. 20, Issue 2, pp. 641-652, 2015.
- [16] J. Martínez, A. García, M. Oliver, J.P. Molina, P. González, "Identifying Virtual 3D Geometric Shapes with a Vibrotactile Glove." *IEEE Computer Graphics and Applications*, Vol. 36, No. 1, pp. 42-51, 2016.
- [17] W.A. McNeely, K.D. Puterbaugh, J.J. Troy, "Six degree-of-freedom haptic rendering using voxel sampling." *Proc. ACM SIGGRAPH*, pp. 401-408, 1999.
- [18] Y. Muramatsu, M. Niitsuma, T. Thomessen, "Perception of tactile sensation using vibrotactile glove interface." *IEEE Cognitive Infocommunications (CogInfoCom)*, pp. 621-626, 2012.
- [19] A.M. Murray, R.L. Klatzky, P.K. Khosla, "Psychophysical characterization and testbed validation of a wearable vibrotactile glove for telemanipulation." *Presence: Teleoperators Virtual Environ.*, Vol. 12, No. 2, pp. 156-182, 2003.
- [20] F.H. Netter, "Atlas of Human Anatomy." 4th ed. USA: Saunders Elsevier Publisher, Section 6: Upper Limb, 2006.
- [21] T. Nojima, D. Sekiguchi, M. Inami, S. Tachi, "The SmartTool: A system for augmented reality of haptics." *Proc. IEEE Virtual Reality (VR)*, pp.67-72, 2002.
- [22] F. Rattay, "Modeling axon membranes for functional electrical stimulation." *IEEE Trans. Biomed. Eng.*, Vol. 40, No. 12, pp. 1201-1209, 1993.
- [23] J.T. Rubinstein, "Analytical theory for extracellular electrical stimulation of nerve with focal electrodes. II. Passive myelinated axon." *J. Biophysical*, Vol. 60, No. 3, pp. 538-555, 1991.
- [24] S. Takei, R. Watanabe, R. Okazaki, T. Hachisu, H. Kajimoto, "Presentation of Softness Using Film-Type Electro-Tactile Display and Pressure Distribution Measurement." *Springer, Haptic Interaction*, Vol. 277, pp. 91-96, 2015.
- [25] E. Tamaki, T. Miyaki, J. Rekimoto, "PossessedHand: techniques for controlling human hands using electrical muscles stimuli." *Proc. ACM Human Factors in Computing Systems (CHI)*, pp.543-552, 2011.
- [26] D. Tsetserukou, S. Hosokawa, K. Terashima, "LinkTouch: A wearable haptic device with five-bar linkage mechanism for presentation of two-DOF force feedback at the fingerpad." *Proc. IEEE Haptics Symp.* pp. 307-312, 2014.
- [27] M. Yamaoka, A. Yamamoto, T. Higuchi, "Basic Analysis of Stickiness Sensation for Tactile Displays." *Proc. EuroHaptics*, pp. 427-436, 2008.
- [28] V. Yem, H. Kajimoto, "Wearable Tactile Device using Mechanical and Electrical Stimulation for Fingertip Interaction with Virtual World." *Proc. IEEE Virtual Reality (VR)*, pp. 99-104, 2017.
- [29] V. Yem, H. Kajimoto, "Comparative Evaluation of Tactile Sensation by Electrical and Mechanical Stimulation." *IEEE Trans. on Haptics*, Vol. 10, No. 1, pp. 130-134.
- [30] V. Yem, R. Okazaki, H. Kajimoto, "Vibrotactile and Pseudo Force Presentation using Motor Rotational Acceleration." *Proc. IEEE Haptics Symposium*, pp. 47-51, 2016.