Pilot Study on Presenting Pulling Sensation by Electro-Tactile Stimulation

Shota Nakayama[1], Mitsuki Manabe[1], Keigo Ushiyama[1], Masahiro Miyakami[1], Akifumi Takahashi[1,2], and Hiroyuki Kajimoto[1]

[1] The University of Electro-Communications, 1-5-1 Chofugaoka, Chofu, Tokyo, Japan
{nakayama, manabe, ushiyama, miyakami, a.takahashi, kajimoto}@kaji-lab.jp
[2] JSPS Research Fellow

Abstract. When an object that is grasped with a finger is pulled by an external force, the traction force is perceived by cutaneous receptors and proprioception in the finger. Several attempts have been made to simulate the pulling sensation by using wearable devices, including mechanical asymmetric vibration and tightening by belt. In this study, we developed a new method that uses electrical simulation to generate an illusory force sensation by simulating the activity pattern of the cutaneous receptors. We validated our method through two experiments, one based on force direction judgment and the other on force magnitude adjustment.

Keywords: Electrical stimulation, Force sensation, Sensory illusion

1 Introduction

Compared to desktop type haptic displays, wearable type haptic displays are not particularly good at presenting external force. To solve this problem, numerous methods that create illusory phenomena by using skin sensation to present force sensation have been proposed.

A typical technique is the use of asymmetric vibration [1–4]. When a weight is vibrated such that it is driven quickly in the forward direction and slowly in the reverse direction, the illusion of being pulled is generated on the hand grasping the transducer. Another typical technique is the use of skin compression [5, 6]. A common method is belt tightening of the finger pad by two motors, which can present the sensation of the finger pad being pressed or the finger sliding sideways. The former technique involves a strong vibration sensation that spreads over the entire hand, whereas the latter requires a large mechanism to be attached around the finger.

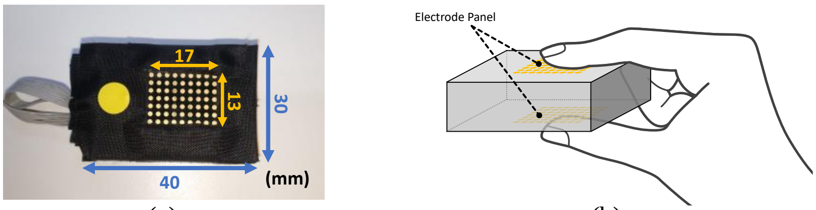
We propose a method to overcome these problems by using a device that presents an illusory force sensation through electrical stimulation. It can be fabricated to be small and thin and does not involve transmitting a vibration sensation to the whole hand. We validated our method through two experiments, one based on force direction judgment and the other on force magnitude adjustment.

2 Method

2.1 Electrical Stimulation Device

Electrical stimulation was performed using the electrical stimulator developed by Kajimoto [7]. This stimulator is divided into a control unit that determines the current and stimulation pattern, and an electrode unit that consists of electrodes and switching circuits. The control unit is connected to a PC through a USB connection.

In the electrode unit (Fig. 1(a)), electrodes are attached to the top and bottom of a small box (4 cm × 3 cm × 1 cm, Fig. 1(b)). Sixty-three (7 × 9) circular electrodes (1.4 mm in diameter) are placed on one electrode board at 2 mm center-to-center intervals. The weight of the complete grasping part is 17 g. The maximum current for electrical stimulation is 6 mA.



(a) (b)

Fig. 1. (a) Electrode unit. (b) Structure of the grasping part.

2.2 Stimulus Pattern

The shallow part of finger skin contains mechanoreceptors called Meissner corpuscles and Merkel cells. Meissner corpuscles are involved in the recognition of object contact and surface texture, whereas Merkel cells identify the pressure sensation [8]. Anodic and cathodic stimulations are two types of electrical stimulations. Anodic stimulation mainly produces vibratory sensation, wherein the stimulating electrode is the anode, and the surrounding electrodes are the cathodes. In contrast, cathodic stimulation mainly produces pressure-like sensation. This is probably because the former tends to stimulate the nerves connected to Meissner corpuscles while the latter tends to stimulate the nerves connected to Merkel cells [9]. This suggests that when an external force is applied to a finger, continuous cathodic stimulation can present the sensation of the finger being pressed against an object. Furthermore, when the finger is in contact or detached, brief anodic stimulation can present the sensation of contact or detachment from the object.

Based on these considerations, we speculated that it was possible to present an illusory force sensation in the intended direction by applying cathodic stimulation to the electrode, and performing anodic or cathodic stimulation for a short period at the beginning and end of the stimulation. In addition, since both aforementioned methods produce stronger illusions at the beginning of stimulation than in steady state, we speculated that we could generate clearer illusory force sensation by repeatedly turning them on and off.

Through trial and error, we discovered a stimulus pattern, shown in Fig. 2, that can be expected to produce an illusory force in the intended direction from the back electrode to the front. The horizontal axis is the elapsed time, and the vertical axis is the value of command current. The discovered pattern consists of the following.

Cathodic stimulation for 400 ms: The cathodic stimulation for 400 ms produces a pressure sensation on one finger. This is the main stimulus to generate the illusory force sensation.

Electrical stimulation at the beginning and end of stimulation: For every 50 ms of stimulus onset and 50 ms of stimulus termination, anodic stimulation is performed on the front surface of the finger. This is expected to produce a situation wherein the front surface of the finger is tapped at the moment of traction. Conversely, cathodic stimulation is performed on the back side of the finger. This stimulation produces an illusory force sensation in the opposite direction for a moment, but the direction of the illusory force sensation changes abruptly in the subsequent 400 ms stimulation, resulting in a more enhanced illusory force sensation.

In this preliminary study, the force sensation in the intended direction was not sufficiently generated by only presenting pressure sensation with cathodic stimulation to one finger. Perceiving it as a clear external force was only possible by combining both stimuli at the beginning and end of the stimulation.

Sato et al. proposed and implemented a method for expressing the sense of contact, edge, and direction of force, by combining the cathodic and anodic stimuli [10]. Our proposed method can be considered as an attempt to generate illusory force sensation by applying this method to the action of pinching with two fingers.

The stimulating electrodes are shown in Fig. 3. The black points were stimulated on both sides 60 times per second (60 pulses per second (PPS)). We reduced the number of stimulation points owing to power and refresh-rate limitations.

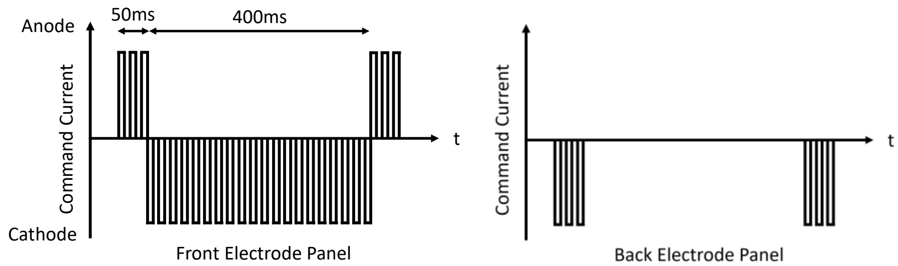


Fig. 2. Proposed stimulus pattern.

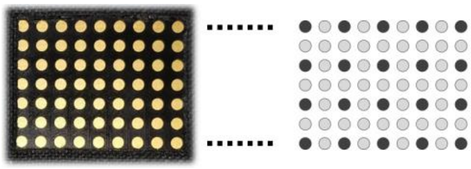


Fig. 3. Electrodes to be stimulated (black points were stimulated).

3 Experiment 1

The purpose of this experiment was to evaluate whether it is possible to create the illusion of traction force in the intended direction through the proposed method.

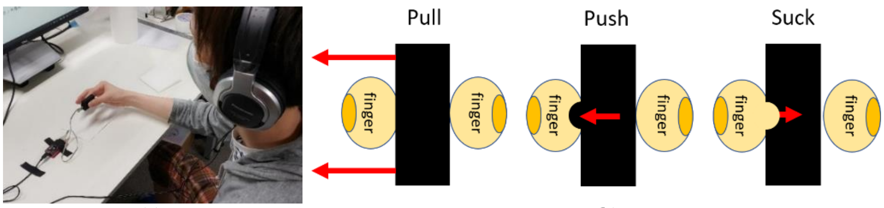
Ten subjects (including four authors), aged 21 through 27, participated in the experiment (Fig. 4(a)). Each subject sat at a desk and held the electrode unit in their right hand. They were instructed to pinch the electrode unit with their index finger on the front surface and the thumb on the back surface. To avoid the effect of moisture, they were instructed to wipe off the sweat from their fingers during the experiment [11]. The experiments were approved by the Ethics Committee of the University of Electro-Communications, Chofu, Tokyo, Japan.

3.1 Experimental Procedure

Subjects were instructed to pinch the electrode unit. While presenting the cathodic stimulus on both sides, the command current value was gradually increased until the subject felt pain. Thereafter, the command current value was lowered and adjusted to the maximum command current value at which the subject did not feel uncomfortable. In addition, we applied the stimulus pattern shown in Fig. 2, without divulging to the subject that it was an experimental pattern, and confirmed that it did not cause discomfort.

The stimulus pattern shown in Fig. 2 was intended to produce an illusory force sensation on the front side of the electrode where the index finger was placed (hereafter referred to as forward stimulus). By switching the stimulus pattern of the front and back electrodes, the illusory force sensation was produced on the back side of the electrode where the thumb was placed (hereafter called the backward stimulus). We presented either of these two stimuli patterns, and in a two-alternative forced choice asked the participants to choose the direction in which they felt the "traction force." The same stimulus pattern was repeated at a frequency of 1 Hz with an interval of 500 ms, until the participants answered. These trials were repeated ten times for each pattern in a random order, for a total of 20 trials. During the trials, the subjects were instructed to hear pink noise on headphones and close their eyes. They were asked to answer the following questions on a 5-point Likert scale (1: not at all, 5: very much).

- Did you feel as if you were being pulled from the outside? (Fig. 4(b) Pull)
- Did you feel as if you were being pushed from the inside? (Fig. 4(b) Push)
- Did you feel as if you were being sucked from the inside? (Fig. 4(b) Suck)
- Did you feel a clear difference between the two stimulus conditions? (Difference)



(a) (b)

Fig. 4. (a) Experimental environment. (b) Definition of force sensation.

After the experiment, the participants were asked to voice their opinions freely.

3.2 Experimental Result

The results of the experiment are shown in Fig. 5(a). The vertical axis shows the overall correct response rates for the forward and backward stimuli, and the error bars represent the standard errors among subjects. A t-test revealed that there was a significant difference from the chance rate (50%) at 5% level (p = 0.003 for the front side and p = 0.047 for the back side).

The swarm and violin plots of the answers to the questionnaire are shown in Fig. 5(b). The horizontal axis shows the questionnaire items, and the vertical axis shows the responses. The dashed lines indicate the quartiles.

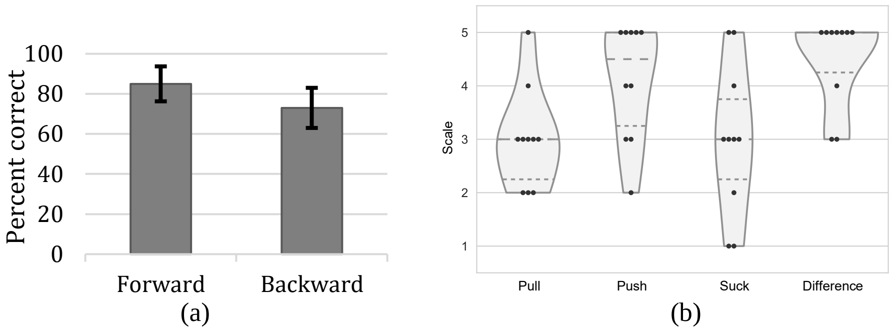


Fig. 5. (a) Experimental result. (b) Questionnaire.

3.3 Discussion

The force sensation was largely generated in the direction we intended. One subject interpreted both front and back stimuli in the opposite directions, whereas three subjects interpreted the forward stimulus almost correctly but tended to interpret the backward stimulus as forward. Furthermore, there was no subject who interpreted the backward stimulus correctly or the forward stimulus as backward. This is presumably because the current threshold was moderately higher in the thumb than in the index finger, and the electrode board used in this study could not cover the thumb completely. Therefore, some subjects might have answered without feeling a clear tactile sensation in the thumb.

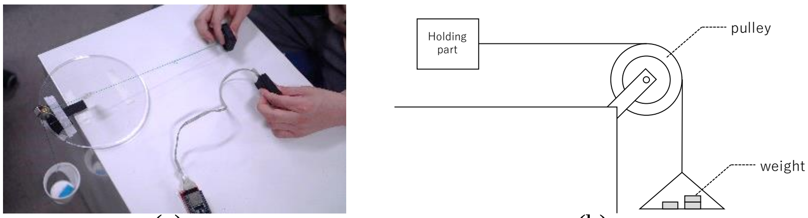
Fig. 5(b) shows that most subjects felt the force sensation of being pushed from inside but not being pulled. Because a typical asymmetric vibration imparts the sensation of being pulled from the outside, the quality of sensation appears to be different and might be insufficient. Considering that the asymmetric vibration incorporates not only skin surface vibration but also joint and deep tissue vibrations, it might be necessary to appropriately stimulate the muscle spindles and Golgi tendon organs related to the fingertips.

4 Experiment 2

The purpose of this experiment was to quantitatively measure the maximum illusory force generated by electrical stimulation, and to compare it with asymmetric vibrations, considering Rekimoto's method [2] as an example of a similar small device. Nine males and one female (including four of the authors), aged 21 through 27, participated in the experiment.

The experimental environment is shown in Fig. 6(a). The subject was seated, and electrical stimulus or vibration was imparted to the left hand, while a physical force was imparted to the right hand. As shown in Fig. 6(b), the physical pulling force was imparted by a string and a pulley with a suspended weight.

The asymmetric vibration was presented by using a short-vibration feedback device (Force Reactor, Alps Alpine). The vibration waveform was a square wave of 2 ms:6 ms, which was found to generate the strongest illusory force sensation by Rekimoto [2]. The drive voltage was 5 V, the absolute maximum rating, and the vibration was repeated for 500 ms with a period of 1 Hz to obtain a similar stimulation pattern as the electric stimulation.



(a) (b)

Fig. 6. (a) Experimental environment. (b) Physical force presentation mechanism.

4.1 Experimental Procedure

The subjects first experienced the vibration and the electric stimulus in order. They held the grasping part in one hand, and the stimulation was performed for approximately one minute. During the stimulation, subjects were told the intended direction of the illusory force sensation. After the experience, they were asked to confirm if the illusory force sensation was generated. This time, all the participants felt the illusory force. Then, the following two measurements were performed. The order of the measurements was counterbalanced.

During the measurement, the subjects were instructed to keep their arms in a floating position above the desk and not move them away from the desk. They then verbally instructed the experimenter to adjust the weight, to obtain the subjective point of equivalence (PSE). The weight was adjusted in 1 g increments. The measurements were repeated three times and the median value was considered as the measured value.

4.2 Experimental Result

Fig. 7 is a slope chart of the measurement results for each subject. The average values of the electric stimulus and asymmetric vibration were 33.2 gf and 45.5 gf, respectively. A t-test revealed a significant difference between the two methods (p = 0.006).

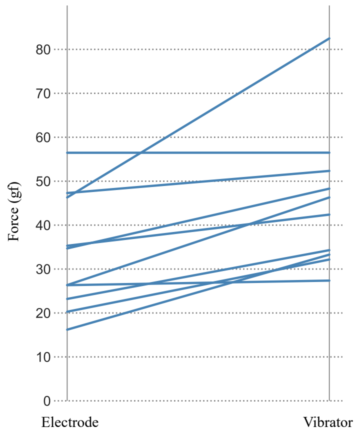


Fig. 7. Strength of illusory force for electrical stimulation and asymmetric vibration.

4.3 Discussion

In this experiment, we compared illusory force sensation presented intermittently with a physical force presented continuously. The illusory force sensation was presented intermittently because presently it is difficult to present a continuous illusory force sensation through electrical stimulation. As a result, a few subjects took a relatively long time to obtain the PSE; eventually all subjects were able to obtain it. In addition, since the illusory force sensation was presented intermittently with the same period for both the electric stimulus and vibration, we believe a that comparison between the two methods is fair.

Regarding the vibration presentation, Rekimoto [2] measured that the average illusory force sensation was 29.8 gf, while our measurement obtained a value of 45.5 gf. The reason for this difference might be that our stimulus pattern was intermittent; hence, the sensory adaptation did not occur. The vibration stimulus produced a larger force sensation than the electric stimulus for all the subjects. As mentioned in 3.3, this may be because of the fact that deep tissues were stimulated by the propagation of vibration but not by the electrical stimulation.

5 Conclusion

This paper examined the possibility of generating illusory force sensation by simulating the activity pattern of receptors, during the action of object grasping, through electrical stimulation. We used electrodes on two sides of a box, front and back, to provide electrical stimulation to the thumb and index finger when grasping the box with them.

As a result, it was established that the proposed method can generate illusory force sensation in a designated direction. However, the quality of the force sensation was different from the expected traction sensation, and the sensation of being pushed from the inside was dominant. Quantitative measurement of the presented force showed that the force sensation was close to that of asymmetric vibration.

In future work, by focusing on the spatiotemporal distribution of skin deformation, we intend to investigate stimulus patterns that produce stronger traction illusion by focusing on the spatiotemporal distribution of skin deformation.

Acknowledgements. This work was supported by JSPS KAKENHI Grant Number JP18H04110.

References

1. Amemiya, T., Ando, H., Maeda, T., “Virtual force display: direction guidance using asymmetric acceleration via periodic translational motion,” in *First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics Conference*, Mar. 2005, pp. 619–622.
2. Rekimoto, J., “Traxion: a tactile interaction device with virtual force sensation,” in *ACM SIGGRAPH 2014 Emerging Technologies*, New York, NY, USA, Jul. 2014, p. 1.
3. Culbertson, H., Walker, J. M., Raitor, M., Okamura, A. M., “WAVES: A Wearable Asymmetric Vibration Excitation System for Presenting Three-Dimensional Translation and Rotation Cues,” in *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, New York, NY, USA, May 2017, pp. 4972–4982.
4. Choi, I., Culbertson, H., Miller, M. R., Olwal, A., Follmer, S., “Grabity: A Wearable Haptic Interface for Simulating Weight and Grasping in Virtual Reality,” in *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology*, New York, NY, USA, Oct. 2017, pp. 119–130.
5. Minamizawa, K., Prattichizzo, D., Tachi, S., “Simplified design of haptic display by extending one-point kinesthetic feedback to multipoint tactile feedback,” in *2010 IEEE Haptics Symposium*, Mar. 2010, pp. 257–260.
6. Chinello, F., Malvezzi, M., Pacchierotti, C., Prattichizzo, D., “A three DoFs wearable tactile display for exploration and manipulation of virtual objects,” in *2012 IEEE Haptics Symposium (HAPTICS)*, Mar. 2012, pp. 71–76.
7. Kajimoto, H., “Electro-Tactile Display Kit for Fingertip*,” in *2021 IEEE World Haptics Conference (WHC)*, Jul. 2021, pp. 587–587.
8. Vallbo, A. B., Johansson, R. S., “Properties of cutaneous mechanoreceptors in the human hand related to touch sensation,” *Hum. Neurobiol.*, vol. 3, no. 1, Jan. 1984, pp. 3–14.
9. Yem, V., Kajimoto, H., “Comparative Evaluation of Tactile Sensation by Electrical and Mechanical Stimulation,” *IEEE Trans. Haptics*, vol. 10, no. 1, Jan. 2017, pp. 130–134.
10. Sato, K., Tachi, S., “Design of electrotactile stimulation to represent distribution of force vectors,” in *2010 IEEE Haptics Symposium*, Mar. 2010, pp. 121–128.
11. Kaczmarek, K. A., Tyler, M. E., Bach-Y-Rita, P., “Electrotactile haptic display on the fingertips: preliminary results,” in *Proceedings of 16th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, Nov. 1994, vol. 2, pp. 940–941 vol.2.