Force Cue Presentation by Electrical Stimulation to Lateral Side of the Finger

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Abstract. It is known that skin deformations on the side of finger contribute to force perception in the fingertip. This study focuses on this knowledge and proposes a method to present force sensation by transcutaneous electrical stimulation via the side of the finger. The compactness of the proposed method makes it suitable for mounting on the fingertip. Moreover, it does not interfere with the tactile sensation of the fingertip, making it easy to combine with other methods such as vibration presentation. Our system is composed of electrodes on the lateral side of fingertip and dorsal surface of middle finger joint. Using this system, we examined the effect of electrical stimulation to the perception of weight during grasping. The results revealed a tendency to perceive the weight of the grasped object to be larger with the stimulation.

Keywords: Electrical Stimulation, Fingertip, Force Perception

1 Introduction

In Virtual Reality and Augmented Reality, haptic feedback is important for improving the quality of interactive experiences. Among them, wearable haptic presentation methods have attracted attention in terms of its convenience. Many wearable haptic presentation methods have been proposed [1], but most of them required large devices such as electromagnetic actuators, especially when force cues are necessary. One solution to this issue is to use electrical stimulation. The electrical stimulation generates tactile sensations by activating mechanoreceptors through electrical current, making it easy to develop a thin and lightweight device.

Previous tactile presentation using electrical stimulation has mainly involved providing cutaneous sensory cues by placing an electrode matrix on the finger pad or by stimulating nerve bundles in the finger with ring-shaped electrodes, or providing force cues by stimulating muscles or tendons. In contrast, we focused on the deformation of the side of the fingers when the finger touches an object. In this case, the finger is compressed between the nail and the contact surface, so not only the finger pad, which is contacting surface, but also the side of finger is deformed. Birznieks et al.[2] reported that activities of mechanoreceptors around the nail contains information of the direction of the force applied to the finger. Based on their findings, we hypothesized that electrical stimulation of the lateral side of the finger could give a force cue. Electrical stimulation of the finger side has the advantage that it does not block the finger pad, therefore it is possible to touch a real object and to combine it with other tactile sensation presentation methods.

To verify whether electrical stimulation of the lateral s of the finger is effective as a force cue presentation method, we developed a clip-type device that can selectively stimulate the left and right sides of the fingertip. In addition, we measured the magnitude of the force cue by using a weight perception experiment.

2 Related Work

A number of wearable tactile presentation methods for fingertips have been proposed [1]. The most concise methods adopted vibration presentation [3–6], but it is difficult to be used as a cue for force sensation. Many attempts to present force sensation to the finger pad squeezed the skin by small actuators [7–11]. There have also been many attempts to miniaturize actuators and present information on the direction of force. Leng [12] proposed to use a folding mechanism to present vibration and pressure sensations to the finger pad only when necessary; Han [13] presented pressure sensations by flowing liquid through a soft tube; Choi [14] used a locking slider to reproduce the sensation of grasping. Minamizawa [15] proposed a tactile presentation method using a belt mechanism; Giraud [16] realized a lightweight pressure presentation mechanism using an origami structure. However, these methods cover the finger pad during tactile presentation, making it difficult to feel the texture of the real object. In an attempt to solve this problem, Maeda [17] developed a device that results in deformation of the finger pad by deforming the side of the finger. However, in general, many methods using actuators require large and complex mechanisms to present the sensation of force, and problems of wearability and durability are likely to arise, especially when deployed on multiple fingers.

In an attempt to miniaturize tactile presentation, a number of methods using electrical stimulation have been proposed in recent years [18–22]. Among them, a method that does not impair tactile sensation at the finger pad by using thin electrodes has been proposed [23]. However, this method requires the attachment of a thin electrode membrane, which is challenging in terms of wearability and durability. Methods that do not cover the finger pad include electric stimulation of the proximal joint of the finger to present tactile sensations to the finger [24] and electric stimulation of the arm [25] . However, these methods stimulate deep nerve bundles, making it difficult to selectively stimulate only the fingertips.

Most electrical stimulation of finger skin aims cutaneous sensations such as vibration and pressure, and rarely targets to present the sensation of force [26] . On the other hand, the sensory presentation of finger force by electrical stimulation has often been performed by electrical stimulation of muscles and tendons present in the wrist and palm [27–30] . However, for electrical stimulation of deep muscles and tendons, relatively large electrodes must be affixed.

An attempt to present the direction of force by electrical stimulation of tactile receptors has been made [31] . They succeeded in reproducing the direction of force by taking into account the strain distribution when a force was applied to the finger pad. Our study similarly presents the sensation of force by electrical stimulation of tactile receptors in the fingertip. However, we investigate the sensation of force by electrotactile stimulation of the side of finger including the vicinity of the nail, based on the physiological findings that there is a high concentration of receptors around the nail [32] and that these mechanoreceptors are active in response to the direction of the force applied to the finger pad [2] . This paper examines the sensation of force by electrotactile presentation to the finger side, including near the fingernail.

3 Apparatus and Stimuli

3.1 Apparatus

The configuration of the electrical stimulator is shown in Fig. 1. The device consists of a control circuit that boosts voltage and regulates stimulation timing, and fingertip electrodes that provide electrical stimulation to the fingertips. The electrodes consist of a gel electrode and a clip with a spring, and they are attached to the thumb and middle finger of the right hand as shown in Fig. 2. The electrodes are arranged in 3 × 4 matrix at 2 mm intervals on both sides, and each matrix functions as a single electrode by short-circuiting the electrodes. This is to ensure a sufficient contact area. The switching circuit in the control circuit allows each electrode to be set to one of three states: high-impedance, anode, or cathode. The total weight of the fingertip device, excluding the cable, is 22 g (including the gel electrode).

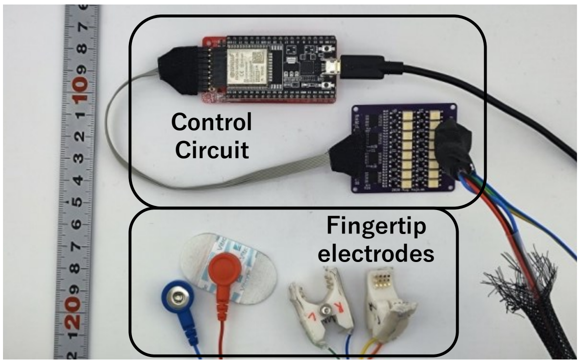

Fig. 1 Configuration of the electrical stimulator.

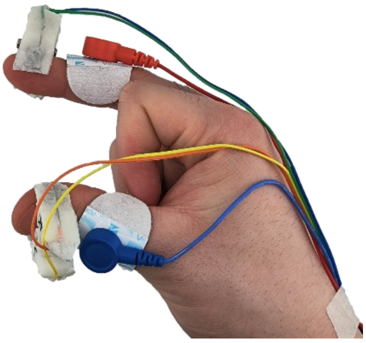

Fig. 2 The electrodes are attached to the thumb and middle finger of the right hand.

3.2 Electrical Stimuli

The electrical stimulation pattern is as shown in Fig. 3. The gel electrode placed on the dorsal side of the finger is always set as an anode. When one of the clip electrodes is set as the cathode, current flows through the finger. Preliminary studies have confirmed that it is possible to stimulate only the area around the clip electrode without generating stimulation that spreads over the entire finger. The reason for this may be that the distance to the clip electrode was not very far, so it was difficult to stimulate the deep median nerve bundle, and the current density of the gel electrode was lower due to its large area. It has also been reported that electrical stimulation of the back of the hand can present tactile sensations solely to the palm of the hand [33].

In the present study, the gel electrode on the back of the finger was always used as the anode and the side of the finger as the cathode, and stimulation of the opposite polarity was not included in the stimulation pattern. This is because the stimulation with the anode on the finger side was felt sharper and difficult to interpret it as pressure or force sensation. The cathodic stimulation of the lateral side of the finger produces a sensation similar to that of pressure, and can be interpreted as a force cue by the interpretation of being pushed [34].

Fig. 4 shows the timing of electrical stimulation. Each finger was stimulated with a pulse of 200 us width every 5 ms, with a delay of 500 us between the middle finger and thumb. This delay was inserted to prevent unintended sensations caused by the current flowing between the two fingers.

As a preliminary study, three subjects (22-26 years old, including one author) were asked about the sensation produced by the proposed electrical stimulation pattern, and it was confirmed that all of them could perceive the stimuli on the left and right sides separately.

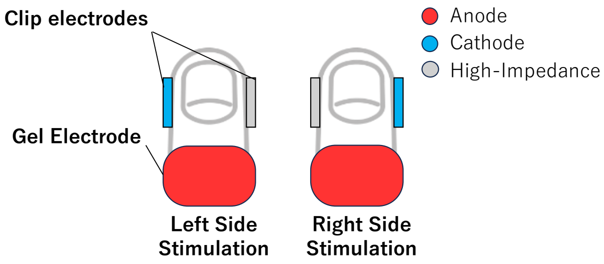

Fig. 3 Stimulus Pattern

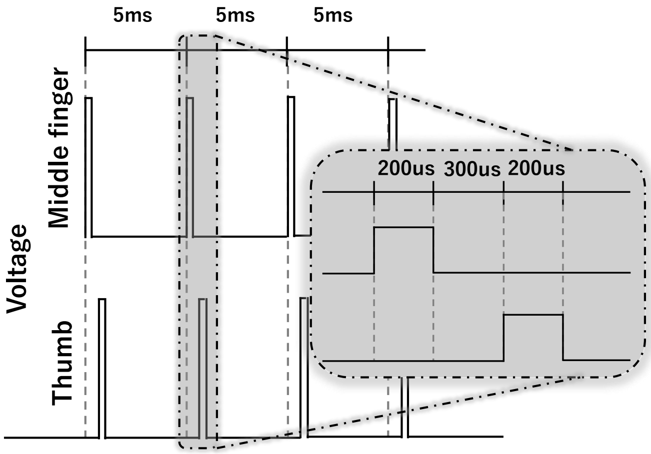

Fig. 4 Timing of electrical stimulation

4 Experiment

In this experiment, we investigated the effect of the proposed electrical stimulation technique on the weight sensation during object grasping. We adopted a constant method to obtaining a subjective equivalence point. This experiment was approved by the Ethics Committee of the University of Electro-Communications.

4.1 Condition

Ten subjects (nine males and one female) aged 22-27 years participated in the study. The reference stimulus was a 200 g weight with three different electrical stimulation conditions (Fig. 5). Comparison stimuli consisted of nine types of weights ranging from 100 to 300 g in 25 g increments. The number of trials was 3 (the electrical stimulation conditions) × 9 (the weight conditions) × 10 (repetitions), for a total of 270 trials. The experiment was conducted over two days.

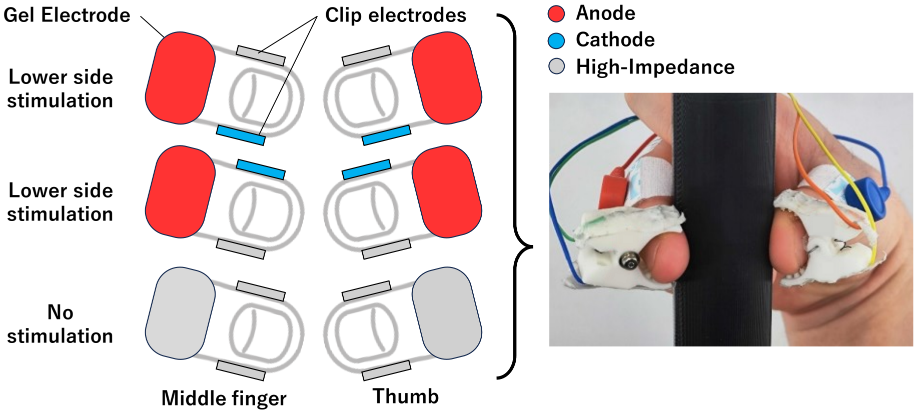

Fig. 5 Electrical Stimulus Conditions

4.2 Setup

The experimental environment is shown in Fig. 6. A cylindrical grip of φ32 mm × 100 mm was placed on a table, and a weight was suspended below the grip. The weight condition was adjusted to the set weight including the gripper and the thread. The weight of the comparison stimulus was varied using a 25 g weight. The reference stimulus weight had a switch mechanism using aluminum foil on its bottom surface, and the electrical stimulation was performed only during the period when the weight was lifted. A plate was placed on the back surface so that the weight loading and weight replacement could not be seen from the subject's side.

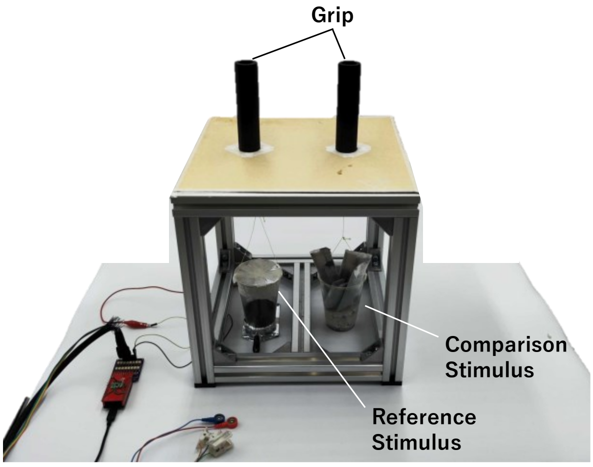

Fig. 6 Experimental Setup

4.3 Method

Adjustment of electrical stimulation intensity. The subjects wore the fingertip device, and for each of the four stimulation sites (left-side and right-side on the thumb and middle finger), the intensity of the electrical stimulation was increased to the maximum within the range that "does not cause pain and does not cause a strong vibration sensation". The stimulus intensity was set to suppress the vibration sensation as much as possible, while making it easy to perceive the force cue. The stimulus intensity was then lowered so that the subjective stimulus intensity was the same across all conditions. These settings were used in subsequent experiments. We confirmed that the differences between the two stimulus sites were perceivable.

Investigation of subjective equivalence points using the constant method. On each trial, the subject was asked to confirm the weight by gently lifting the right and left grips directly upward. The subject's wrists were in contact with the platform in order to suppress the influence of the proprioception of the arms. No restrictions were placed on the order of lifting, the number of times, or the duration. The subjects were then asked to verbally choose which they felt was heavier, the left or the right. Auditory cues were blocked by ear muffs during the experiment.

5 Result & Discussion

5.1 Result

The results are as shown in Fig. 7. The fitting curves were obtained by logistic regression, and the colored areas represent 95% confidence intervals. The subjective equivalence point was 222 g in the lower stimulus condition, 225 g in the upper stimulus condition, and 203 g without stimulus.

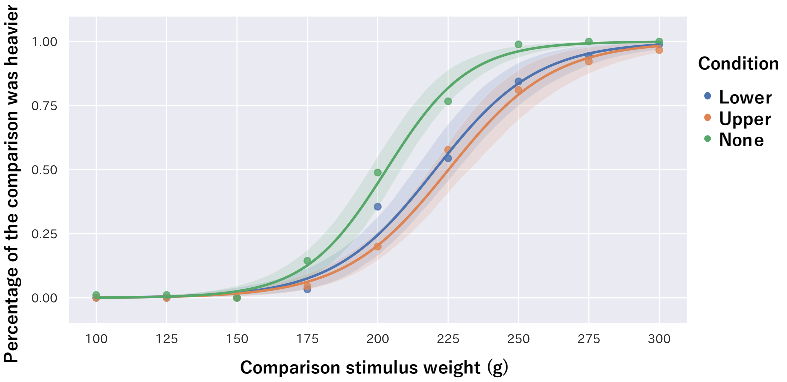

Fig. 7 Results

5.2 Discussion

The subjective equivalence points of Fig. 7 was about 220 g for both the lower and upper stimulation conditions, whereas it was almost 200 g for the no-stimulus condition, indicating that the subjects perceived more weight under both electrical stimulation conditions. The method to generate force-cue by asymmetric vibration of a relatively compact transducer [35] is known to generate a maximum force of about 0.6N, suggesting that the proposed method can generate a force of the same order without interfering with the finger belly, although the magnitude of the force is not as large.

In addition, the proposed method is considered to stimulate afferent fibers that lead to mechanoreceptors on the lateral side of the finger, suggesting that people may use these mechanoreceptors as cues for weight perception when grasping an object. It implies importance of reproducing not only the contact area but also the surrounding skin area in order to realize a higher quality tactile presentation.

In 3.2, we hypothesized that "cathodic stimulation of the lateral side of the finger produces a sensation similar to that of pressure, which is perceived as if the finger is being pressed. Given this hypothesis, we expected that stimulation of the lateral side of the finger would in some cases produce a larger perception of weight (heavier) and in other cases a lesser perception of weight (lighter). In fact, however, we did not find any phenomenon in which the lower stimulus condition made the weight perception of the grasped object lighter. There were three possible reasons for this.

The first one is that the weight of the reference stimulus was so heavy that it was difficult to perceive lightness. In a study of asymmetric vibration, it has been reported that only relatively lightweight vibrators produce the illusion of upward traction [36]. This suggests that the use of a heavy weight (200 g) may have prevented the upward traction illusion. However, it is difficult to explain the reason for the perception of heavier weight for the lower stimulus.

The second explanation is that the other somatosensory factors had a larger contribution to the weight perception. In this experiment, the subject's wrists were in contact with the desk, so it is possible that the pressure sensation around the wrists contributed to the perception of weight. Although this may explain relatively small amount of weight change, it also does not explain the reason for the perception of heavier weight for the lower stimulus.

The third explanation is that discrepancies in interpretation caused by electrical stimulation of the lateral side of the fingers. When a heavy object is grasped, one side of the finger is compressed and the other side is stretched. Both this compression and extension have the same skin strain energy and may be difficult to distinguish. Therefore, it is possible that weight perception was determined only by the amount of stimulation of the lateral surfaces. In other words, in order to make the subject feel lighter, neural activity would have to be "reduced," which would be difficult to do with the current setup.

Although this experiment was conducted under conditions of no stimulation and stimulation of each side of the finger, the possibility that weight was judged simply by the amount of stimulation (total amount of tactile sensation) cannot be dismissed.

Therefore, a comparison with the case in which electrical stimulation was applied to the finger belly, or comparison with vibrotactile stimulation should also be considered.

It is also possible that the difference in weight sensation originates from finger fatigue (influenced by which stimulus was lifted first) or the perception of short-time memory (influenced by the time of lifting). Furthermore, since the subjects were very male-biased, the presence or absence of gender differences needs to be investigated.

Force presentation by asymmetric vibration does not require the vibration to be preloaded (weighted). Experimental results do not indicate that the proposed method can present such a force even without a weight, and this needs to be investigated. Experimental results also show that the subjective sense of weight increases with stimulation on both the upper and lower sides. This result can be interpreted as electrical stimulation lowering the threshold of the receptors, which may hinder its application in VR and AR.

6 Conclusion

Inspired by the finding that receptor activity around the fingernail encodes the direction of force, we proposed a method of presenting force perception by electrical stimulation to the lateral side of the finger. To quantitatively verify the magnitude of the force cue that the proposed method can realize, we examined the change in weight sensation during object grasping. The results showed that stimulation to the finger side can generate a force sensation equivalent to that of the asymmetric vibration-based force-cue presentation method, which has been studied previously. However, contrary to our expectation, the weight was always perceived as changing toward the heavier side, and no change toward the lighter side was observed.

As a future prospect, we will verify the effectiveness of the method as tactile feedback. Specifically, we will verify the effectiveness of the combination of electric stimulation to the finger belly. In parallel, we will also focus on the spatiotemporal changes in the strain of the entire finger when force is applied to the finger, and investigate electrical stimulation patterns that generate a higher quality sense of force.

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