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Force Rendering via Electrical Stimulation of Fingernail and Finger Pad

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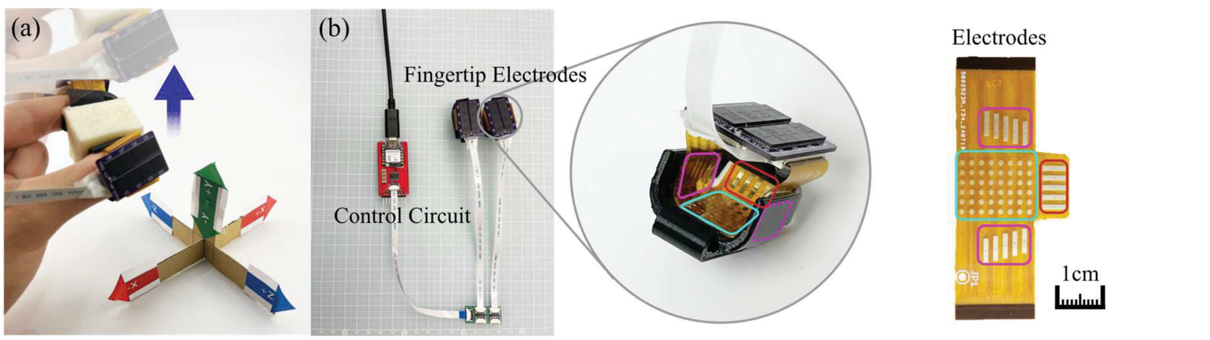

Fig. 1. (a) Illustration of the system concept and experimental setup. Directional force sensations are rendered through electro-tactile stimulation. (b) The custom-designed electro-tactile interface for two fingers, with a magnified view highlighting electrode placement. The electrodes on the flat part of the finger pad are circled in light blue.

***Abstract*—Previous neurophysiological studies have revealed that the strain around the nails significantly contributes to the perception of force at the fingertips. Based on this finding, this study presents a novel method for achieving multi-degree-of-freedom force presentation. The proposed approach applies electro-tactile stimulation to the entire fingertip, including its lateral sides. The effectiveness of the proposed method was evaluated through two experiments. Experiment 1 assessed whether force perception was present in three degrees of freedom—front-back, up-down, and left-right—using electrical stimulation. Experiment 2 investigated the role of electrical stimulation around the fingernail in contributing to force perception. The results suggest that the proposed method facilitates multi-degree-of-freedom force perception. Furthermore, electrical stimulation around the fingernail was identified as a crucial factor in producing force sensation.**

Keywords—Electro-tactile Display, Force Perception, Wearable Devices

I. Introduction

In recent years, the demand for high-precision haptic representation has increased across various domains, including entertainment, medical rehabilitation, and remote work support [1][2]. Wearable haptic presentation methods are anticipated to play a significant role in VR/AR environments due to their compact form and ability to support a wide range of motion. Numerous systems have been proposed to address these needs [3][4][5][6]. However, most of these systems rely on mechanical moving parts, such as electromagnetic actuators, which make them large and difficult to implement in a fully wearable setup, particularly when force feedback is required.

Electrical stimulation offers a promising solution to this challenge. Since it requires only the attachment of electrodes to the skin, this approach enables the development of thin and lightweight wearable devices.

Previous approaches to haptic presentation with electrical stimulation have used electrode arrays on the fingers and hands to deliver cutaneous sensation cues [7][8][9][10][11]. Additionally, methods have been proposed to produce force sensations by stimulating muscles and tendons [12][13][14][15]. For presenting a sense of force, electrodes must be placed on the forearm or other areas containing muscles, rather than on the fingertips. Consequently, achieving a sense of touch, encompassing both skin and force sensations, requires electrodes in two distinct locations—the fingertips and the forearm—complicating the device's wearability.

Here we focused on the deformation of the lateral side of the finger when it touches an object. When the finger makes contact, the nail causes deformation not only in the finger pad which is the contact surface, but also in the lateral side of the finger. Birzniek et al. [16] reported that mechanoreceptors around the nail are sensitive to the direction of force presented to the finger. Their findings suggest that stimulating the lateral side of the finger could provide a force cue.

This study explores the possibility of creating multi-degree-of-freedom force sensations by presenting electrical stimulation to both the lateral side of the finger (around the nail) and the finger pad. This approach aims to present a "strain sensation around the nail" and a "pressure sensation on the finger pad" simultaneously, making the haptic device compact.

II. Related Work

In wearable haptic feedback systems, physically representing external forces is challenging. This limitation arises from the need for a body-anchored fulcrum to generate force, with the reaction force being perceived at the fulcrum. To address this issue, many methods have been developed to create pseudo-haptic feedback through illusions based on skin sensations.

One common approach involves asymmetric vibration [17][18][19][20]. Moving a weight forward quickly and backward slowly during vibration creates the illusion that the hand holding the device is being continuously pulled forward. Another method relies on skin pressure [21][22][23][24]. Han et al. [25] developed a technique to produce pressure sensations by flowing liquid through a flexible tube. Minamizawa et al. [26] introduced a tactile presentation method with a belt mechanism, while Giraud et al. [27] developed a lightweight pressure system using origami structures.

To make haptic feedback systems more compact, researchers have proposed methods to create force sensations using electrical stimulation [12][28][29]. These methods often involve stimulating the muscles and tendons in the wrist and palm. However, stimulating deeper muscles and tendons requires relatively large electrodes, which increases the number of presentation sites needed.

Several attempts have been made to represent the direction of force compactly using electrical stimulation without large electrodes [30][31]. Sato et al. [30] reproduced the direction of force by analyzing the strain distribution on the finger pad when force was presented. Other studies focus on presenting the direction of force rather than its perception. For example, Jiang et al. [31] presented the direction of force by presenting continuous electrical stimulation to the side of the finger.

Based on neurophysiological findings that the area around the fingernail contributes to the perception of force [16], Nakayama et al. [32] investigated subjective weight perception through psychological experiments involving electrical stimulation of the lateral finger surface. Their results showed that a 200 g weight was perceived as approximately 20 g heavier under stimulation. Xu et al. [33] further demonstrated that mechanical stimulation of the fingernail's lateral surface could evoke a sense of force. However, no studies have attempted to provide multi-degree-of-freedom force sensations using electrodes that cover the entire finger.

III. Methods

In Experiment 1, we tested the accuracy and confidence levels of force perception in six directions (forward, backward, upward, downward, right, and left) using electrical stimulation. In Experiment 2, we examined the role of electrical stimulation around the fingernail in force perception. The experimental setup is shown in Fig. 1 (a). All the experiments were conducted with the approval of the Ethics Committee of the University of Electro-Communications, Japan (No. H24046).

A. Apparatus

Fig. 1 (b) shows the electrical stimulation device used in this study [34]. The device comprises a microcontroller for control, a voltage booster circuit, a voltage-to-current conversion circuit, a switching circuit that assigns the specified electrode as either a cathode or an anode, and a fingertip electrode.

The system comprises 63 electrodes configured in two patterns: a grid arrangement on the finger pad ($6 \times 8 = 48$ points) and an array arrangement on the side and front of the finger ($5 \times 3 = 15$ points). The distance between electrode centers is 2 mm. Electrodes on the pad are 1 mm in diameter, whereas those on the side and front measure 1 mm × 5 mm. The larger size of the side and front electrodes ensures effective stimulation near the fingernail, regardless of finger size, as this area is crucial for producing force sensations. Each electrode can function as either an anode or a cathode. The fingertip electrodes weigh 21 g, excluding the cable.

In the experiment, electrical stimulation was presented while the participant grasped a 30 mm × 25 mm × 30 mm cuboid urethane block with the thumb and index finger on either side, and haptic stimulation was provided. The urethane block (EXSEAL Corporation, super-soft modeling resin [milky white], H5-100) weighed 23 g. The experiment was designed to facilitate the recognition of the presented sensation as a force by establishing a clear "holding" context. Notably, most of the research on force presentation using asymmetric vibration introduced in Section II was conducted while holding the vibrator.

B. Electrical Stimuli

The experiment employed only cathodic stimulation, omitting stimulation of the opposite polarity. This decision was based on the observation that anodic stimulation resembles vibration and is less likely to be perceived as pressure or force. In contrast, cathodic stimulation induces a pressure sensation that can be interpreted as a pushing force, providing an effective cue for force perception [35]. The stimulation protocol utilized cathodic stimulation with a pulse width of 50 µs. At any given time, one electrode was designated as the cathode, with all surrounding electrodes functioning as anodes. By alternating the active cathode every 200 µs, a spatial stimulation pattern was generated. The stimulation sequence was delivered at a rate of 100 pps (pulses per second) per electrode.

C. Experiment 1

The objective of Experiment 1 was to evaluate the capability of the proposed method to represent force direction through electrical stimulation. Ten participants, including two females and eight males aged between 21 and 26 years, took part in the experiment. Of these, eight were right-handed, and two were left-handed.

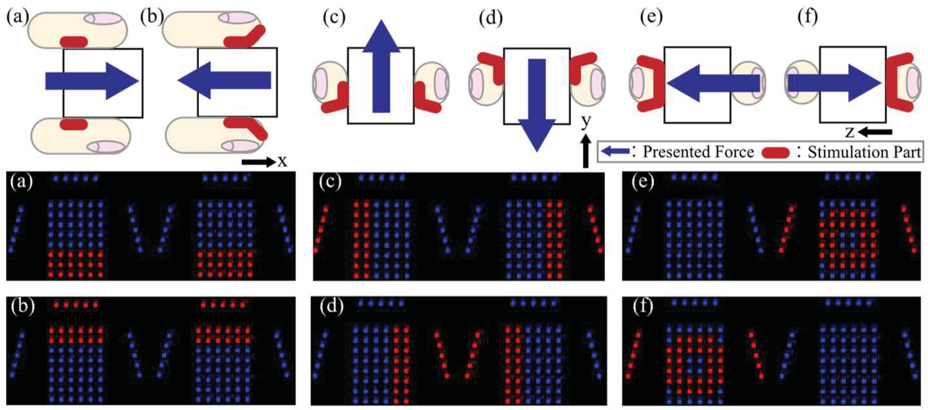

Fig. 2. The stimuli presented in Experiment 1. The left-side electrodes are for the index finger, and the right-side electrodes are for the thumb. (a) Front Force: Stimulus simulating a force in the front direction. (b) Back Force: Stimulus simulating a force in the back direction. (c) Up Force: Stimulus simulating a force in the up direction. (d) Down Force: Stimulus simulating a force in the down direction. (e) Right Force: Stimulus simulating a force in the right direction. (f) Left Force: Stimulus simulating a force in the left direction.

Six stimuli were presented as shown in Fig. 2. The purpose of each stimulation pattern is as follows.

- (a), (b): To induce a forward force, stimulation was presented to the anterior half of the palmar surface of both the thumb and index finger. This stimulation was expected to evoke the sensation of the entire finger being pushed forward. To induce a backward force, stimulation was presented to the anterior half of the palmar surface of the thumb and index finger, as well as the region around the fingernail tip. This combination of stimulation was expected to evoke the sensation of the entire finger being pushed backward.
- (c), (d): Regarding vertical forces, for example, when a downward force is presented to the grasped object, the point of contact between the fingers and the grasped object moves slightly upward, and it is expected that the area around the fingernails will also be stressed. For this reason, we stimulated the upper half of the thumb and index finger in the grasping posture, hoping to induce the sensation of a downward force.
- (e), (f): In the case of lateral forces, grasping the urethane block from the left and right causes alternating pressure on the pads of the thumb and index finger, which is expected to induce strain around the fingernail regions. By presenting these stimuli, we aimed to elicit a perceived force in the lateral direction.

In the front-back and up-down directions, cathodic electrical stimulation was presented in an ON/OFF pattern with a 1-second cycle. For the left-right direction, the stimulus gradually spread outward from the center and returned within the same 1-second cycle. This type of stimulus was selected based on a previous study [36], which used a similar gradually spreading stimulus on an array-type electro-tactile display.

In the experiment, the participant's left index finger and thumb were used. The procedure began with the adjustment of the electrical stimulus intensity using a moving vertical line stimulus pattern. The participant could adjust the intensity using a keyboard and was instructed to make the stimulus as strong as possible without causing pain. During the experiment, the participant was allowed to modify the stimulus intensity at any time using the keyboard. This adjustment was implemented to account for the potential reduction in sensitivity to electrical stimulation caused by perspiration during the experiment. It ensured that the stimulus intensity remained at a level where the tactile sensation was consistently perceivable. As shown in Fig. 1 (a), the participant was instructed to hold the urethane block and align it with the XYZ axis during stimulation.

Prior to the main experiment, six types of stimuli, as depicted in Fig. 3, were presented: Front Force (stimulus directed toward +X), Back Force (stimulus directed toward -X), Up Force (stimulus directed toward +Y), Down Force (stimulus directed toward -Y), Right Force (stimulus directed toward +Z), and Left Force (stimulus directed toward -Z). These electrical stimuli were tested to ensure clear perception from the area around the fingernail to the finger pad. Participants were not informed of the expected correct responses during this adaptation phase. Only participants who could clearly perceive the stimuli proceeded to the main experiment, which involved ten participants.

The experimental procedure was as follows: Participants were presented with a stimulus and asked to identify the perceived direction from six options: +X, -X, +Y, -Y, +Z, and -Z. Additionally, they rated their confidence in their response using a Likert scale ranging from 1 (not at all confident) to 7 (very confident). Each participant completed 30 trials in random order, with five trials for each stimulus type.

D. Experiment 2

The goal of Experiment 2 was to determine whether electrical stimulation around the fingernail contributes to the perception of haptic sensations. The same 10 participants from Experiment 1 also took part in Experiment 2.

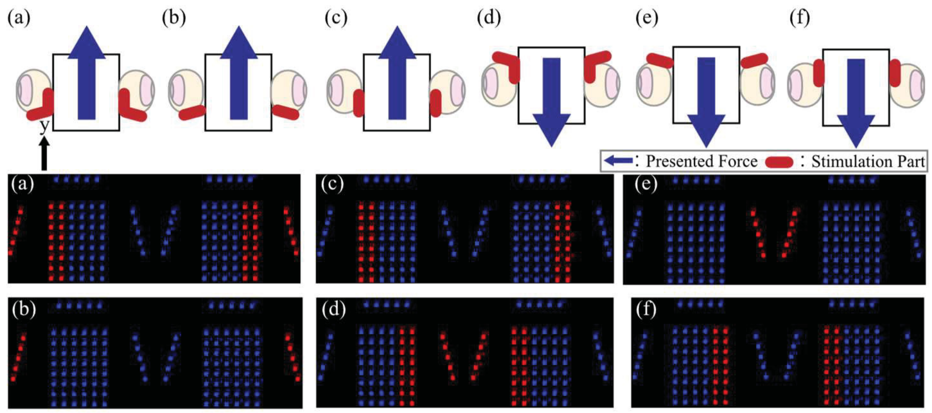

Fig. 3. Stimuli presented in Experiment 2. The left-half electrodes are for the index finger, and the right-half electrodes are for the thumb. (a) Up_all: Stimulated the finger pad and around the fingernail to simulate a force in an upward direction. (b) Up_nail: Stimulated only around the fingernail. (c) Up_pad: Stimulated only the finger pad. (d) Down_all: Stimulated the finger pad and around the fingernail to simulate a force in a downward direction. (e) Down_nail: Stimulated only around the fingernail. (f) Down_pad: Stimulated only the finger pad.

Six types of electrical stimulation, illustrated in Fig. 3, were presented. To reduce the duration of the experiment, the simulated force was limited to the vertical direction. The purpose of each stimulation pattern is as follows.

- (a), (d): Similar to Experiment 1 (Fig. 2 (c)(d)), it was expected that stimulating both the area around the fingernail and part of the finger pad would create a sensation of force in the vertical direction.
- (b), (e): Stimulation was presented only to the area around the fingernail. If the area around the fingernail contributes to the perception of force, a sensation of force was also expected in this case.
- (c), (f): Stimulation was restricted to a part of the fingerpad, with no stimulation presented to the area around the fingernail.

As in Experiment 1, the adjustment procedure was also the same as in Experiment 1.

Prior to the main experiment, six types of stimuli, as depicted in Fig. 3, were presented: three directed toward +Y (Up_all, Up_nail, Up_pad) and three directed toward -Y (Down_all, Down_nail, Down_pad). These electrical stimuli were tested to ensure clear perception from the area around the fingernail to the finger pad. Participants were not informed of the expected correct responses during this adaptation phase.

The experimental procedure was as follows: Participants were presented with a stimulus and asked to identify the perceived direction from six options: +X, -X, +Y, -Y, +Z, and -Z. Additionally, they rated their confidence in their response using a Likert scale ranging from 1 (not at all confident) to 7 (very confident). Each participant completed 30 trials in random order, with five trials for each stimulus type.

IV. Results

Data from all experiments were statistically analyzed for correct response rates and confidence levels. The Shapiro-Wilk test was first conducted to determine whether the correct response rates followed a normal distribution. The test showed that the data were not normally distributed. Therefore, in Experiment 1, the Wilcoxon signed-rank test, a non-parametric method, was used to compare the correct response rate to the chance rate (16.7%) to evaluate the statistical significance of different stimulus conditions for presenting force sensations. In Experiment 2, the Friedman test, another non-parametric method, was applied to determine whether there were significant differences in correct response rates among stimulus conditions. The analysis aimed to demonstrate that the combination of "nail stimulation + finger pad stimulation" significantly enhances the perception of force, making it feel more tangible rather than merely representing directional cues. While "finger pad stimulation" alone may suffice for direction perception, the addition of nail stimulation increases the likelihood of interpreting the sensation as an actual force.

The Shapiro-Wilk test was also conducted to determine whether the confidence levels of the responses followed a normal distribution. The results indicated that the confidence levels did not follow a normal distribution. Therefore, the Friedman test and post-hoc test, both non-parametric methods, were used for analysis in Experiment 1 and Experiment 2. These tests were employed to determine whether significant differences existed in confidence levels among the various stimulus conditions.

A. *Experiment 1: Evaluation of Force Discrimination and Confidence with Six Directional Stimuli*

Fig. 4 illustrates the correct response rates for each stimulus condition in Experiment 1. The Wilcoxon signed-rank test was conducted to compare the observed response rates to the chance rate (16.6%), revealing significant differences for Front Force ($p = 0.04$), Back Force ($p = 0.011$), Up Force ($p = 0.0054$), Down Force ($p = 0.0054$), Right Force ($p = 0.0052$), and Left Force ($p = 0.0053$). Fig. 5 depicts the confidence levels associated with responses for each stimulus condition in Experiment 1. Analysis using the Friedman test indicated no significant differences in confidence levels among the stimulus conditions.

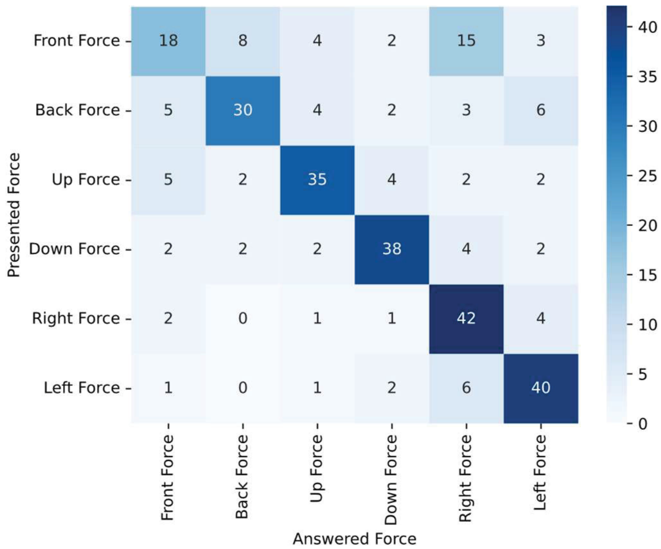

Fig. 4 Confusion matrix of response results for each condition. (Experiment 1)

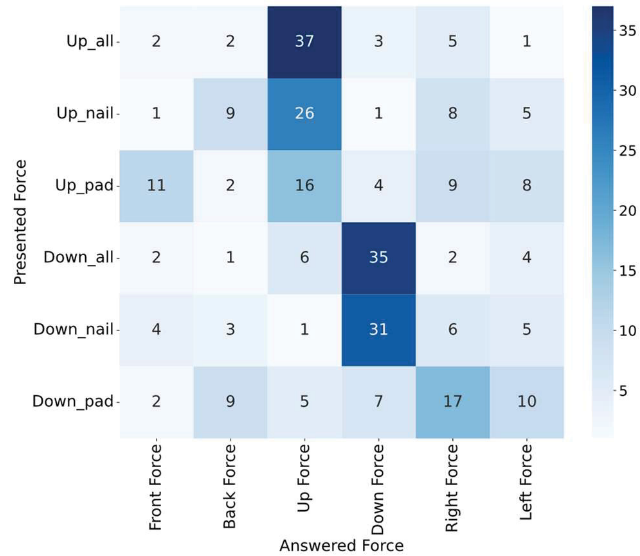

Fig. 6. Confusion matrix of response results for each condition. (Experiment 2)

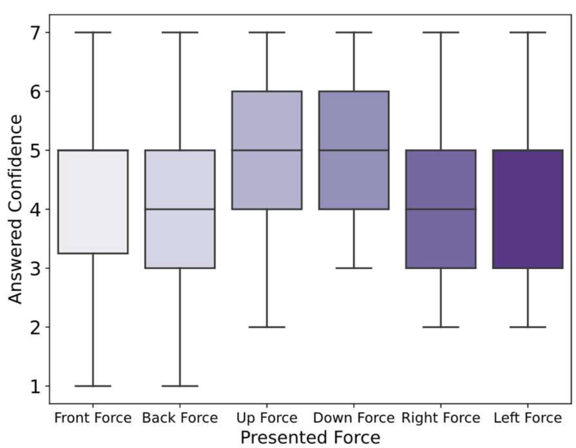

Fig. 5. Confidence levels in directional responses to electrical stimulation. (Experiment 1)

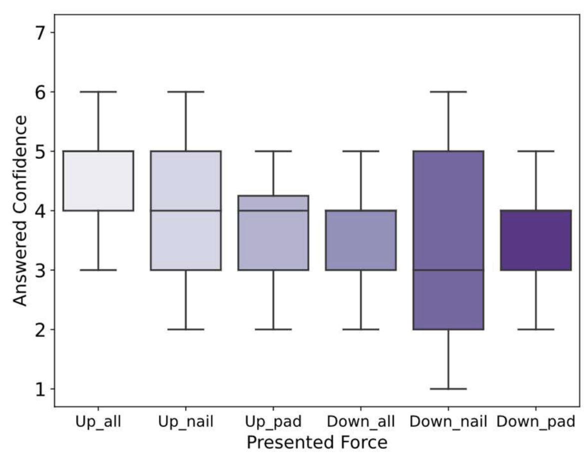

Fig. 7. Confidence levels in directional responses to electrical stimulation. (Experiment 2)

B. *Experiment 2: Evaluation of Force Discrimination and Confidence with Six Directional Stimuli*

Fig. 6 illustrates the correct response rates for each stimulus condition in Experiment 2. The Friedman test identified a significant effect of the electrical stimulus conditions ($p = 1.62$ e-0.5). Post-hoc analysis revealed significant differences between the following pairs: Up_all and Down_pad ($p = 0.001$), Up_pad and Down_all ($p = 0.047$), Down_all and Down_nail ($p = 0.033$), and Down_all and Down_pad ($p = 0.001$). Fig. 7 shows the confidence levels for responses under each stimulus condition in Experiment 2. While the Friedman test demonstrated a significant effect of the electrical stimulus conditions ($p = 0.0094$), the post-hoc test did not identify any significant differences.

V. Discussion

A. *Presenting Directional Force*

In Experiment 1, the correct response rate for all stimulus patterns was significantly higher than the chance rate, suggesting that the force sensation was successfully conveyed to some extent. The correct response rate exceeded 80% for Left and Right Forces and surpassed 70% for Up and Down Forces, demonstrating that participants were able to accurately and unambiguously identify the direction of the presented force.

It is important to note that the correct response rate for Front Force was significantly lower compared to the other stimuli. This might be due to the difficulty in interpreting the stimulus on the back half of the fingertip as a Front Force. In contrast, the correct response rate for Back Force was relatively high, likely because the end-of-finger stimulus near the fingernail could be interpreted as a force pushing the entire finger backward. There was no statistically significant difference in confidence levels among responses. This is likely because confidence ratings depend heavily on the subjective judgments of each participant. These findings highlight the need for further standardization and the incorporation of objective measurement methods to enhance the reliability of confidence assessments.

B. *Stimulation Patterns on Up-down Force Perception*

In Experiment 2, six conditions were tested to represent the sensation of vertical force: three conditions for upward force (stimulating the finger pad and around the fingernail, only around the fingernail, and only the finger pad) and three corresponding conditions for downward force.

When only the finger pad was stimulated, the Down Force was frequently misperceived as a Right Force. A similar effect was observed in the Front Force condition of Experiment 1, which may be attributable to the thumb pad's orientation, as it is not perfectly parallel to the index finger. Conversely, in the condition simulating Up Force by stimulating only the finger pad, they most frequently chose Up Force. This suggests that stimulating the finger pad alone can generate a sense of force to some extent.

Stimulating only the area around the fingernail evoked a clearer perception of vertical force compared to stimulating only the finger pad. These findings suggest that electrical stimulation of the fingernail region is an effective approach for presenting vertical force direction. This result contrasts with a previous study by Nakayama et al. [32], which reported that stimulating the area around the fingernails while grasping an object made the object feel heavier and did not allow control of the force direction (not lighter). A potential explanation for this difference is the variation in object weight. In the current experiment, a 23 g urethane block was used, whereas Nakayama et al. used a 200 g object as a reference. Studies on asymmetric vibration have reported that the illusion of an upward pull can only be induced with a relatively light vibrator [20]. This suggests that the inability of previous research to accurately represent force direction may have resulted from the use of heavy objects.

Finally, it was confirmed that the most distinct haptic sensation was produced when the nail area and the finger pad were stimulated simultaneously. This outcome is likely due to the complementary interaction between the two stimuli, enhancing the perception of force. While finger pad stimulation alone generates a weak haptic sensation, and nail area stimulation alone produces some force, their combination creates a synergistic effect that significantly enhances the haptic perception of force. These findings support the hypothesis and demonstrate the effectiveness of simultaneous stimulation of the nail area and the finger pad in creating distinct haptic sensations.

C. *Limitation and Future Work*

One key limitation of the current approach is its inability to convey forward-direction force sensations. Since the stimulation is essentially delivered in an on/off manner, it fails to capture the subtle, continuous nature of real-world force sensations. To better replicate these forward-direction forces, it will be necessary to develop more refined stimulation methods that gradually change over time. Such improvements should enhance the distinctness and realism of the perceived force sensations. Variations in individual finger morphology may have led to incomplete contact between the electrodes and the skin. To address this issue, the use of stretchable electrodes that can flexibly conform to each user's finger shape is considered desirable.

Another significant avenue for future exploration is the presentation of force sensations during active manipulation. For example, it is important to study the sensations experienced when the object being grasped is shaken or tilted by presenting stimulation around the fingernails. Incorporating haptic sensations that reflect active manipulation could enable participants to perceive not only changes in weight but also dynamic sensations, such as the presence of liquid in a container or shifting loads.

It remains unclear whether users genuinely perceive the direction of the presented force or merely infer it based on the stimulated location. Clarifying this distinction represents an important direction for future research. Moreover, we intend to investigate the cognitive load involved in identifying both the direction and to explore the level of force this method can render.

VI. Conclusion

This study introduced a novel approach to compact multi-degree-of-freedom force presentation by combining electrical stimulation of the lateral side of the finger (around the fingernail) and the fingertip. This method simultaneously delivered a “stretch sensation around the fingernail” and a “pressure sensation on the fingertip.” Based on neurophysiological evidence that skin deformation on the lateral side of the finger contributes to force perception at the fingertip, this method utilized electrodes covering the entire finger to enable 3-DOF force presentation.

Experimental results validated the accuracy of force presentation across six directions: front-back, up-down, and left-right. Correct response rates exceeded 60% in five directions, excluding the front force, and all stimulus patterns demonstrated significantly higher correct response rates than the chance rate, indicating successful presentation of force sensations. Furthermore, the findings highlighted the importance of simultaneous stimulation of the fingernail area and the finger pad in enhancing the clarity of up-down force sensations. While finger pad stimulation alone proved insufficient for generating a clear force sensation, the combination of fingernail and finger pad stimulation resulted in a pronounced haptic sensation.

These findings underscore the potential of electrical stimulation for force sensation presentation and offer a new direction for the development of haptic interfaces that leverage skin deformation at the fingertips.

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