3D Shape Presentation by Combination of Force Feedback and Electro-tactile Stimulation

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***Abstract*—The rapid and precise understanding of 3D objects in virtual reality environment is crucial for proficient manipulation of virtual objects. Generally, relying solely on a force feedback device falls short in conveying intricate shapes, such as the edges of 3D objects, and it is deemed necessary to supplement it with appropriate cutaneous sensory inputs. Electro-tactile stimulation, owing to its compact and lightweight design, has the potential to provide high-resolution cutaneous sensory inputs and could be a viable method for presenting intricate shapes when incorporated with a force feedback device. In this research, we devised a system that concurrently presents cutaneous inputs along the object's edge through electrical stimulation, as well as reactive force from the object through a force feedback device, and evaluated its impact on 3D shape perception under three scenarios: force feedback alone, cutaneous feedback alone, and combined sensory presentation. The results from experiments on the identification of four types of column shapes in single-finger contact and two-fingers grasping indicate that the combined presentation of force and electro-tactile sensation significantly hastens the differentiation time of the shapes and facilitates more efficient recognition of 3D objects.**

***Keywords*—3D shapes, electro-tactile display, haptics, virtual reality**

I. INTRODUCTION

Haptic feedback enriches the realism of interactions in virtual reality (VR) and enhances the immersion of the user's experience. Specifically, the haptic rendering of virtual object shapes is imperative for fostering intuitive engagement through touch and grasp of objects within the virtual environment.

The sense of touch encompasses two broad categories: cutaneous sensory perception at the skin surface and deep sensory perception (force perception) at muscles, tendons, and joints. During manual exploration of an object, both cutaneous and deep sensory perceptions are activated [1]. Studies have demonstrated the feasibility of facilitating dexterous manipulation of virtual objects through the provision of either cutaneous or force sensation tactile feedback [2][3]. Conversely, it has been reported that force feedback devices encounter challenges in conveying the intricate shapes of objects, such as microbumps and edges, which are local features that impede the shape recognition process [4][5]. In particular, Cutaneous vibration cues play a crucial role in discriminating micro-uneven shapes when dynamically rubbing the surface of an object with a finger [6][7][8]. Thus, the conveying of intricate shape information necessitates the integration of cutaneous feedback, such as pressure distribution on the contact surface, with force feedback, requiring the force feedback device to be equipped with a mechanism for cutaneous feedback.

While existing force feedback devices have already enabled precise rendering of virtual object shapes through force feedback, precise reproduction of cutaneous sensation remains a challenge due to the low resolution of the presented stimuli. Furthermore, integrating a mechanism for presenting intricate shapes through cutaneous sensation onto an existing force feedback device is complicated, as it leads to an increase in size and complexity of the system.

Electro-tactile displays can serve as a useful means for delivering high-density cutaneous sensation in a compact and detailed manner. With the ability to present cutaneous sensations at 2 mm intervals, and their compact and thin design, electro-tactile displays can be easily integrated onto the end of existing force feedback devices. Currently, there is a lack of comprehensive verification of the presentation of shapes through the combination of force and electric stimulation.

In this study, we aim to enhance the accuracy and speed of 3D shape perception of virtual objects by rendering force feedback of virtual objects through a force feedback device and presenting cutaneous sensation of the object's edges using an electrical stimulator. To evaluate the effectiveness of this combined presentation, a column shape recognition task is conducted and the results are compared to those of single sensory presentation of force or cutaneous sensation.

II. RELATED WORK

A typical tactile interface for shape presentation is in the form of a pin array placed on a tabletop that is driven to physically render a shape [9][10][11]. These pin-array displays afford users to touch the shape with their entire hand, enabling the reproduction of pressure distribution as well as force presentation. However, there are inherent physical limitations to incorporating physically driven pins, and the spatial resolution is challenging to enhance due to the configuration of the device. Another form involves the utilization of finger-mounted actuation devices to produce shape representations [12][13][14]. The wearable design allows for a large workspace but also presents challenges due to its large and complex structure.

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2023 IEEE World Haptics Conference (WHC)
WHC 2023, Delft, Netherlands, July 10–13, 2023

Adding a structure capable of providing cutaneous cues would further complicate the design.

Various proposals have been put forth to convey 3D shapes solely through cutaneous stimulation, including full-hand vibrations [15], electrical stimulation applied to the thumb and index finger [16], and ultra-high resolution air pressure to the entire finger [17], all of which have demonstrated efficacy in facilitating shape recognition with cutaneous stimulation alone. However, it requires more time to recognize shapes using only cutaneous cues, as compared to when force cues are also involved, which is crucial for intuitive and quick handling of shapes. While some research has sought to supplant force cues with cutaneous cues [18], it has been established that while simple tactile tasks can still be accomplished with accuracy and stability, a lack of actual force presentation results in decreased interaction reality and a diminished sense of presence [19][20], making it unsuitable for more intricate teleoperation tasks, such as tele-surgery.

The perception of a surface shape with slight macroscopic unevenness of a few millimeters is heavily influenced by force cues, surpassing other cues such as the position and tilt of the finger in the world coordinate system [21]. Additionally, the presentation of the finger tilt cue has been found to be more significant in conveying the curvature of irregular shapes than the finger position cue [22]. The integration of both force and tilt cues has been established to enhance the accuracy of shape perception [23][24]. Fingertip position and tilt cue presentation and surface shape presentation using pin arrays have also been realized in handheld devices [25].

Various studies have been proposed to combine both force and cutaneous cues for shape presentation. Adding vibration stimuli to the force presentation mechanism has been shown to enhance shape presentation and improve manipulation accuracy [26][27][28][29]. The proposal of simultaneous force presentation and pneumatic stimulation has improved performance in targeting tasks [30]. Further, an interface with distributed tactile presentation at the end of a force feedback device has been demonstrated to improve manipulation accuracy during grasping tasks [31], and to enhance accuracy in tracing 3D surface geometry [32].

As for the combination of force and electro-tactile presentations for shape rendering, a prior study have demonstrated the efficacy of incorporating electro-tactile cues to enhance grasp manipulation in a virtual reality setting [33]. Sato et al. [34] [35] were pioneers in combining force and electrical stimuli for shape presentation. They performed surface shape presentation by adding electrical stimuli to force stimuli on a real object, and showed that the fusion of force and electrical stimuli may be efficient for shape presentation. They have successfully developed a remote tactile shape transmission system that combines force feedback and electrical stimulation to reproduce the sensation of one-dimensional pressing with a single finger [36], and have expanded the technology to include five-finger presentation [37]. However, there remains a lack of research investigating the individual contributions of force feedback and electrical stimulation to shape presentation. Trinitatova et al. [38] demonstrated the ability of a teleoperated system to feedback both force and electrical stimulation for accurate and efficient task performance. With advancements in the miniaturization of electric stimulators and increasing density of stimulation points [39][40][41], electric stimulation is poised to offer increasingly refined shape presentation. However, a comprehensive examination of the impact of integrating force feedback devices with electrical stimulators for 3D shape presentation has yet to be conducted.

III. METHOD

Fig. 1 illustrates the apparatus utilized in the present study, which presents both force feedback and electrical stimulation concurrently. A desktop force feedback device, Touch X USB (3D Systems), was used for force feedback in consideration of stability of presentation, accuracy of sensing, and ease of control. This force feedback device allows for 6-degree-of-freedom operation of an end-effector, with the ability to render a 3D shape within a workspace of 355 W × 228 H × 180 D millimeters. For the purpose of delivering force and cutaneous feedback to the fingertips, an electrode and finger insert mount have been attached to the end-effector in place of the traditional stylus. The electrical stimulation device in Fig. 1 is a pulse generation system similar to the one used by Kajimoto [39]. It consists of 64 electrodes arranged in a finger-shaped configuration on a flexible film-like substrate, with slits that allow the electrodes to deform to fit the curved surface of the fingertip. The device is designed to present stimulation on one finger or two fingers by providing two units 53.0 mm apart horizontally.

The force feedback was rendered using the Haptics Direct for Unity plug-in, integrated with the Unity game engine. The electrical stimulation was rendered by a group of 64 objects that reproduces the actual electrode arrangement in the Unity scene. The objects followed the pointer object of the Touch X USB and were detecting contact with an object in the scene. Fig. 2 shows that the information of the electrode touching the object's edge was sent to the microcontroller (ESP-WROOM-32) via serial communication and anodic stimulation was applied to the corresponding electrode. This implementation applied electrical stimulation only at the edges of the object, as the cutaneous intensity being stronger at the edges is a natural phenomenon considering elastic mechanics, and in a pilot study, when all electrodes in contact with the object were stimulated with electricity, it was found that the stimulation amount was too high, which could become a hindrance to force feedback.

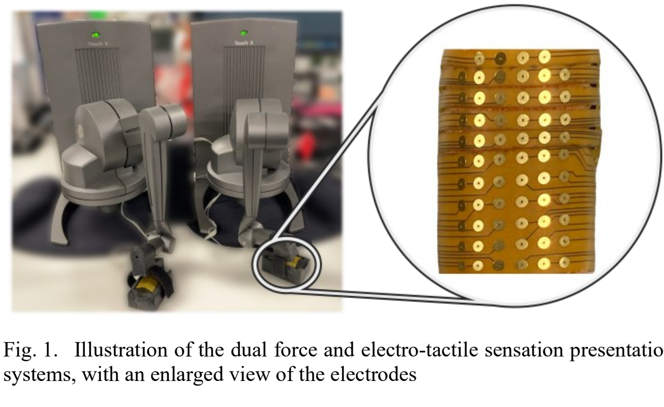

Fig. 1. Illustration of the dual force and electro-tactile sensation presentation systems, with an enlarged view of the electrodes

Fig. 2. Force and electro-tactile rendering; the 64 electrodes attached to each of the two devices, the green circle represents the electrode that is in contact with the edge of the presented object (in the center of the monitor), and the corresponding electrode is being stimulated.

IV. EXPERIMENT

The experiment was designed to evaluate the accuracy of 3D shape discrimination inspired by a previous study [16] that used only electrical stimulation to present 3D shapes. 12 participants (11 males, 9 right-handed, 22-24 years old, with an average age of 23.2) took part in the experiment. Of the 12 subjects, ten had experienced force feedback and electro-tactile stimulation involving a singular index finger. However, none of the participants had experienced force and electro-tactile sensations utilizing both the thumb and index finger during grasping actions. The shapes presented in the experiment were square, circular, hexagonal, and triangular prisms, each designed to have a cross-sectional thickness of 15.0 mm, as shown in Fig. 3. The cross-sectional thickness was sufficient to ensure that the presenting parts of the two devices would not interfere with each other. Each shape was drawn in the middle of the two presenters in Fig. 1, with the height of each shape drawn as infinite. This means that the top and bottom surfaces of each shape were drawn outside the workspace of the device, so that the force and cutaneous sensation was only presented at the side of each shape. As described in Section III, the electrical stimuli were presented only when touching the edge of the object (green area in Fig. 3), but for the circular prism, the entire surface was drawn as an edge, considering it as a shape consisting of an infinite number of corners.

The experimental process was divided into two parts: the practice phase and the discrimination phase. In the practice phase, participants practiced touching the shapes while they were visible on the software (as shown in Fig. 2), and the intensity of the electrical stimulation was adjusted to produce a sufficient cutaneous sensory perception without causing pain for each participant. Participants dedicated approximately 5 minutes to familiarize themselves with shape presentations under concurrent force feedback and electro-tactile stimulation conditions, engaging in shape recognition practice for all forms. After the practice was ended, the participants moved on to the identification phase. During the identification phase, the shapes were presented without visual feedback, and participants were asked to identify the presented shapes. Their responses and response times were recorded. The participants had to identify the four column shapes presented under three different stimulus conditions: electrical stimulation only, force only, and the combination of force and electrical stimulation. Each shape presented by each feedback was presented three times in a random order, for a total of 36 presentations. The shapes were always presented in the same orientation as in Fig. 3. The sequence of trials was considered one set, and two sets were performed, one with the index finger of the dominant hand and one with the thumb and index finger of the dominant hand.

Six participants performed the first set of trials with one finger and the second set with two fingers, while the remaining six participants performed the opposite. After the first half of the trials, the participants took a sufficient rest before starting the second half.

The experiment was approved by the ethics committee of the authors' institution.

Fig. 3. Four types of prisms presented in the experiment. Green areas are drawn as edges, and electrodes touching the green areas are electrically stimulated.

V. RESULT

The results of the participants' responses for each stimulus condition when using one or two fingers are summarized in the confusion matrices in Fig. 4.

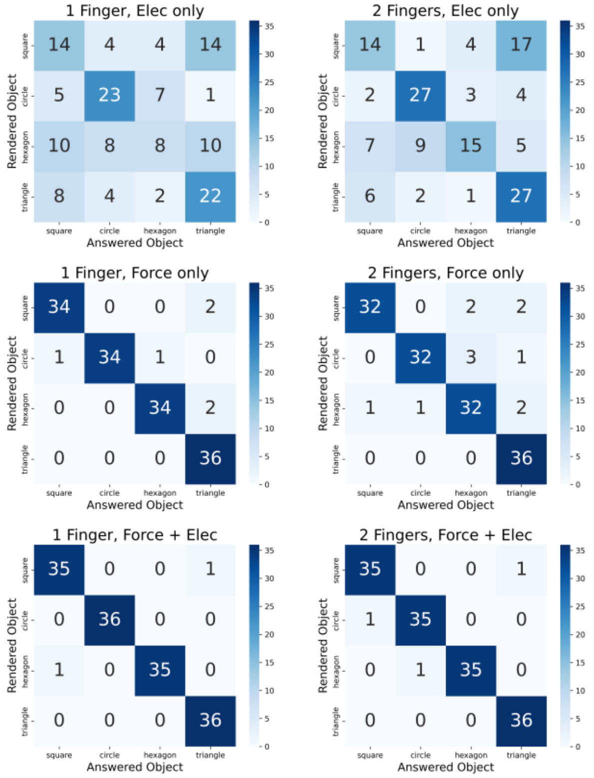

Fig. 4. Confusion matrices of response results for each condition

A two-way repeated-measures analysis of variance (ANOVA) on the correct response rate with two factors, touch and stimulus type, revealed no interaction (*p*=0.072), no main effect of touch type (*p*=0.373), and a main effect of stimulus type (*p*=0.000).

The Bonferroni multiple comparisons for stimulus type showed significant differences between the electric-only and force-only conditions (*p*=0.000), and between the electric-only and force+electrical stimulation conditions (*p*=0.000). No significant difference was found between the force-only and force+electrical stimulation conditions (*p*=0.177).

T-tests confirmed a significant difference (*p*=0.000) for all conditions compared to the chance rate (25%) for each index.

Fig. 5 summarized the response times for each shape and presentation condition, which were normalized to have a maximum value of 1.0 for each participant, since the response time varied greatly among subjects. The following analyses were also conducted on the normalized values. The real time data (mean ± standard deviation) shows the longest response time was 67.9 ± 36.7 seconds and the shortest was 5.09 ± 1.74 seconds.

The results of the two-way repeated measures ANOVA for each shape on response time with two factors, touch and stimulus type showed no interaction between touch and stimulus type (p-values for square, circle, hexagon, triangle: *p*=0.472, *p*=0.963, *p*=0.789, *p*=0.236), no main effect of touch type (*p*=0.144, *p*=0.065, *p*=0.144, *p*=0.059), and a main effect of stimulus type (*p*=0.000, *p*=0.000, *p*=0.000, *p*=0.000).

The Bonferroni multiple comparisons for stimulus type revealed significant differences in response time between the electric-only and force-only conditions (*p*=0.001, *p*=0.039, *p*=0.000, *p*=0.000), as well as between the electric-only and force+electrical stimulation conditions (*p*=0.000, *p*=0.001, *p*=0.000, *p*=0.000) for all shapes. There were significant differences between the force-only and force+electrical stimulation conditions for circle (*p*=0.013), hexagon (*p*=0.038) and triangle (*p*=0.027) shapes, but no significant difference for the square shape (*p*=0.071).

The participants provided the following comments on the experiment:

- "I relied mainly on the force cue to discriminate the shape and did not use the electric stimulation cue." (P3, P7)
- "It was challenging to perform the trials in the electric-only condition as there was no force cue, but it was possible to get correct answers with enough time." (P1)
- "The only shape that could be identified with electric stimulation alone was circular prism as stimulation was applied on all its sides." (P4, P5)
- "The addition of electrical stimulation to the force cue made it easier to identify the edges and recognize shapes, increasing my confidence in my responses. However, the tactile sensation of the electrical stimulation was not realistic and was used only as a symbolic cue to locate the edges." (P4, P7, P8)

VI. DISCUSSION

This study investigated the ability to identify 3D shapes using one-finger touch and two-finger grasp, under different conditions of electric stimulation, force-only, and force+electrical stimulation.

The results showed no significant difference in shape discrimination accuracy or response time between one-finger touch and two-finger grasp. Although it is commonly believed that two-finger grasp is better for shape perception, this experiment used primitive and symmetrical shapes without changing orientation, which may have made the shape cues perceived by one and two fingers similar. Current methods for assessing cutaneous sensations are inadequate, necessitating further validation in future research.

The results of the study showed that the accuracy of shape identification was highest for the force-only and force+electrical stimulus conditions, and was significantly higher than for the electric stimulation-only condition. However, there was no significant difference between the accuracy of shape identification in the force-only and force+electrical stimulus conditions, with both conditions yielding an average correct response rate of over 90%. In this setup, the presented shapes had a relatively large thickness of 15.0 mm to prevent interference with the force feedback devices, and it is believed that the subjects were able to perceive shapes with enough detail using only force cues. The effect of shape perception with a

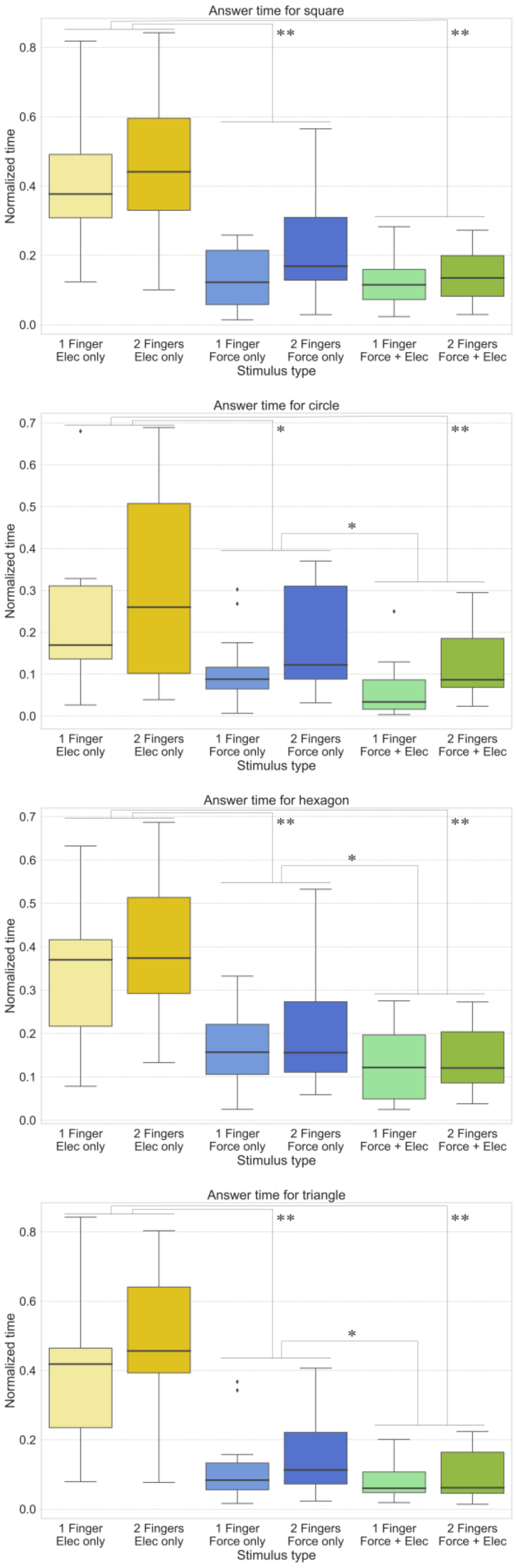

Fig. 5. Response time for each shape in each presentation condition

thickness of only a few millimeters needs to be verified in the future. The shape discrimination accuracy with electric stimulation alone was lower compared to the presentation conditions including force sensation. However, the average correct response rate was about 50%, which was significantly higher than chance rate (25%), indicating that shape presentation with electric stimulation alone is possible. However, Fig. 4 shows that the circle shape, which had the most stimulus points, and the triangle shape, which had the fewest, had relatively high correct response rates in shape identification with electric stimulation, suggesting that identification might have been based on symbolic cues like the amount of stimulation and that perception may have been more sensitive with more shape presentations. The circle shape, when presented exclusively through electrical stimulation, was distinctly more stimulating compared to other shapes, potentially resulting in a high proportion of accurate responses. Nevertheless, approximately 30% of the responses were erroneous. This is likely due to participants' inability to fully trace the shape's surface under the sole influence of electrical stimulation, perceiving interruptions in stimulation when not in contact with the shape as a discontinuity in the edge, leading to misidentification of the shape.

The shape identification time was shorter for force-only and force+electrical stimulation compared to electrical stimulation only. This was because it was difficult to judge the shape's location intuitively with electrical stimulation only, as only the shape's edges were presented. The identification time was shorter for force+electrical stimulation than force-only for most shapes except square. This showed that adding electrical stimulation to force presentation was effective in presenting the shapes. However, participants commented that the edge sensation presented by the electric stimulation was not realistic, but only symbolic. This may be due to uniform stimulation intensity at the electrodes touching the edges. For example, among the shapes presented here, the triangular, square, hexagonal, and circular columns have sharp edges in that order, but the presented edges were far from realistic as they did not represent differences in stress concentration and pressure distribution. We need to use finite element analysis to calculate the amount of deformation of the finger model and apply stimulation with an intensity proportional to that value to obtain a more realistic impression of the edges. Furthermore, if anti-aliasing by stochastic stimulation of electrical stimulation, which was used in a study that attempted shape presentation by electrical stimulation [16], is introduced, shape presentation with higher resolution might be achieved. The presentation of a realistic edges by electrical stimulation is an issue for further investigation. Furthermore, the achievable resolution through electrical stimulation requires thorough analysis and technical evaluation.

Although participants commented that the addition of electrical stimulation to the force presentation increased their confidence in their responses, it is not possible to discuss the effect on subjective experiences such as confidence, because we only evaluated the correct response rate and task execution time in this experiment. These evaluations will be necessary in future studies.

VII. CONCLUSION

This study presented a system that combined force feedback and electric stimulation to present 3D shapes. The results showed that the combined presentation method was more effective in shape discrimination compared to force-only or electric stimulation-only presentation, as evidenced by shorter identification times. Further research is needed to explore the effects of modulating electric stimulation intensity for more realistic edge presentation since the simple edge presentation by electric stimulation is symbolic and has low realism. In addition, it is necessary to conduct quantitative and qualitative evaluations, with more variation in object shapes including much smaller objects with have small-amplitude-high-spatial frequency surfaces, and by performing a task in which the objects are handled in a more realistic environment.

ACKNOWLEDGMENT

This research was supported by JSPS KAKENHI (Grant Numbers JP20H05957).

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