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Perception of Finger Angle Position in Grip-type Haptic Display based on Grasping Force

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Abstract: In this study, we propose a novel grip-type haptic display for controlling a virtual (or robotic) hand (Fig. 1). This grip-type haptic display enables us to control a virtual hand and perceive haptic information based on a reactive force and a spatially distributed tactile feedback. Because this proposed display does not need any actuators to produce the reactive force, a simple haptic display is developed. In a grip-type haptic display, it is difficult to perceive the finger position because of the fixed position of the user's fingers. However, we consider that it is possible to perceive the finger position by means of the effort exerted. Therefore, we performed an experiment to discriminate the applied force and confirm that the force discrimination threshold was sufficiently small. Then, we constructed a one-fingered prototype using an electrotactile display. Using this prototype, we qualitatively confirmed that the reactive force with the spatially distributed tactile feedback can produce dynamically changing haptic information.

Keywords: Haptics, RT System and Integration, Network and Virtual Reality Systems

1. INTRODUCTION

A haptic display for hand is sought for the gentle and dexterous manipulation of a grasping object in telepresence (or telexistence) and virtual reality technologies. The haptic display presents the following two types of information: kinesthetic information (through proprioception) and tactile information (through cutaneous sensation). In the kinesthesia, the sense of position, posture, and movement of a limb, are important for controlling the grasping force that applied to an object in order to perceive its properties such as size, weight, and softness. In the case of tactile information, the sense of the distribution of pressure and vibration on the skin surface, is mainly perceive us the contact condition between the skin and the object. Therefore, tactile information is important to perceive texture and exact shape of the object.

There are three requirements for the haptic display for hand. First, the haptic display should measure the complex motions of the fingers and reflect them into a virtual (or robotic) hand. This enables us to control the virtual hand as if it was the user's hand. Second, the haptic display should produce both kinesthetic and cutaneous sensations to multiple fingers. To achieve a gentle and dexterous manipulation, both forms of feedbacks are important. The third and final requirement is that it should be highly usable. As a human-machine interface, it should be easily used by everyone, regardless of age and sex.

Thus far, a number of haptic displays have been developed, however, they don't satisfactorily fulfill the abovementioned requirements. For example, a wearable haptic display that consists of an encounter-type master hand and an electrotactile display has been developed [1]. This haptic display can measure the motion of user's fingers and present both kinesthetic and electrotactile sensation. However, because of the complicated mechanical parts needed to produce kinesthetic sensation, the usability of the device is not good. Not only does the size of the device limit the user but also it is cumbersome to wear and difficult to control. Meanwhile, CyberTouch [2] does not produce force feedback and it comprises compact wearable haptic displays. The usability of the haptic display is improved; however, its size still limits the user. Furthermore, gentle grasping is difficult because of the lack of kinesthetic sensation. Another type of haptic display is a grip-type haptic display. We can easily use the grip-type haptic display by simply grasping it. It can measure the finger movement by means of button or force input. We have also developed a cylindrical force sensor called "MeisterGRIP" as a robotic hand control system [3]. This sensor can measure the grip force of each finger in terms of three-dimensional force vectors. However, haptic feedback is minimally recognized as only a reactive force. Therefore, it is difficult to recognize contact of an object and distinguish its properties.

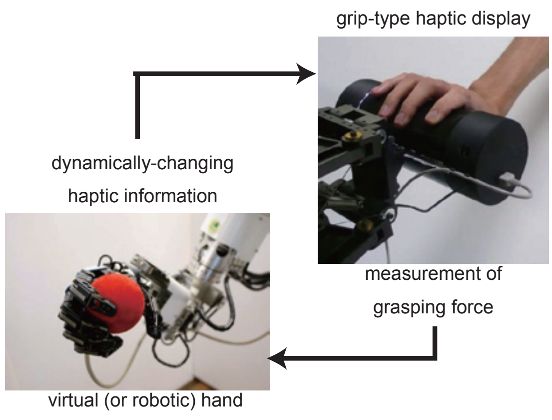

Fig. 1 Conceptual diagram of grip-type haptic device.

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In this study, we propose a novel grip-type haptic display with a tactile feedback for controlling a virtual hand (Fig. 1). We consider integrating conventional grip-type haptic display with a tactile display that can present spatially distributed pressure sensation. This integration allows the haptic display to satisfy all the abovementioned requirements. However, it seems difficult to control the position of a virtual finger based on the grasping force. Furthermore, it also seems difficult to produce dynamically changing haptic feedback. In this study, we investigate the force discrimination threshold to confirm the possibility of controlling of a virtual finger. Then, using a one-fingered prototype, we qualitatively examine the possibility of producing dynamically changing haptic sensation.

2. GRIP-TYPE HAPTIC DISPLAY

In this chapter, we introduce the methods for controlling a virtual finger and the haptic feedback of the grip-type haptic display. Fig. 2 shows the principle of the grip-type haptic display that we propose. This display measures a user's grasping force for controlling a virtual hand. Haptic feedback is provided in the form of a reactive force from the device with a spatially distributed tactile display.

2.1 Control of a virtual finger

A wearable haptic display measures the user's finger joint-angle positions θ_v to transmit it to virtual finger's positions θ_h when the virtual finger does not touch an object (Eq. (1)).

$$\theta_v = \theta_u \tag{1}$$

Therefore, the user can control the position of the virtual finger as if it were his/her actual finger. When the virtual finger touches an object, the user's applied force vector f_u to the haptic display is reflected to the virtual finger's force vector f_v (Eq. (2)).

$$f_v = f_u \tag{2}$$

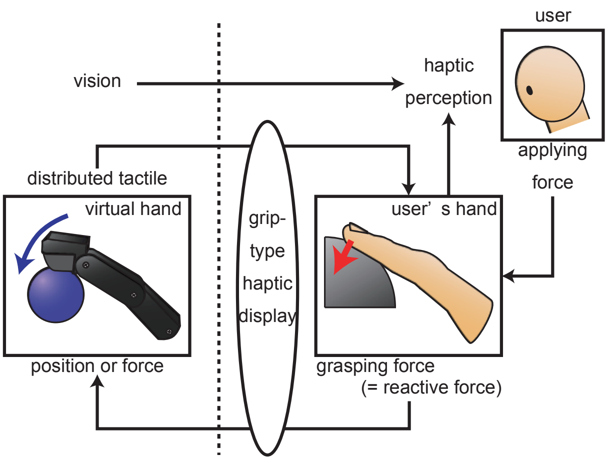

Fig. 2 Proposed grip-type haptic display.

Therefore, the user can also control the grasping force of the virtual finger.

In contrast, our grip-type haptic display measures the force applied to the device by the user's finger and transmits it to the position and force of the virtual finger. When a user tries to move the virtual finger, the movement of the user's finger causes the muscle of the user's finger to contract. Then, the grip-type haptic display measures the force applied by the fingertip. The measured grasping force is then transmitted to the joint-angle positions of the virtual finger when the virtual finger does not touch an object.

$$\theta_v = f(f_u) \tag{3}$$

In Eq (3), $f(\cdot)$ represents the conversion function from the grasping force to the joint-angle positions of the virtual hand. Each finger of human has three joints and four DoF (Degree of Freedom). However, the DoF can be approximated by three [4] [5]. Therefore, we can control the position of virtual finger using three-dimensional force vector. Meanwhile, when the virtual finger touches an object, the measured grasping force is transmitted to the force of virtual finger as in a conventional haptic display (Eq. 2).

In proposed control method, the position of the user's fingertip is not displaced. Therefore, it seems difficult to control the joint-angle positions of the virtual finger. However, we consider that the user can perceive the joint-angle positions of the virtual finger through his/her own sense of effort expended to move the finger. When the user tries to move the virtual finger, he/she expends the force into each joints of the finger. This force sensation can help perceive the joint-angle position of the virtual finger.

It should be noted that we use a low range of grasping force to control the virtual finger. When the user controls the virtual finger, he/she perceives some reactive force exerted by the device. This sense of resistance increases when the user applies a large force. Furthermore, when the virtual finger touches an object, we have to control the grasping force with the offset force that is applied to control the position of the virtual finger. Therefore, a large grasping force is not suitable for controlling the virtual finger. We must also consider that the elastic body of the device and the visual feedback can reduce this sense of resistance. If the device has an elastic body, the displacement of its surface is expected to reduce the resistance. Furthermore, visual feedback is also considered to play an important role in haptic perception [6]. Therefore, the resistance will be further reduced when the user watches the movement of the virtual hand.

2.2 Tactile feedback with reactive force

An ideal haptic display presents three-dimensional force and tactile information to the user when the virtual finger touches an object. In this case, the user can control the grasping force and easily perceive the properties of the object.

In contrast, when the user grasps the grip-type haptic display, he/she sense only the reactive force exerted by the device. Based on this reactive force, the user can control the grasping force of the virtual hand. However, this reactive force is always transmitted in the same direction and amplitude, regardless of the object grasped by the virtual hand. Therefore, the user cannot perceive the properties of grasped object. Furthermore, the user cannot recognize contact with an object in the absence of visual feedback.

To overcome this difficulty, we integrated the spatially distributed tactile feedback with a reactive exerted by the device. The spatially distributed tactile information is of fundamental importance to the perception of contact with an object and the sensing its physical properties. For example, the distribution of pressure on the skin surface represents the exact shape, position, posture, and softness of an object [7]. We consider tactile information compensates for the poor haptic feedback of conventional grip-type haptic displays.

3. DISCRIMINATION OF FORCE

In the grip-type haptic device, the user recognizes the joint-angle position of the virtual finger through his/her sense of effort expended to move the joints of the finger. Therefore, the performance of force perception of each joint is quite important. Especially, to bend the virtual finger like as human's finger, we have to recognize the applied force of PIP (Proximal Interphalangeal) and MCP (Metacarpophalangeal) joints independently. Therefore, in this experiment, we examined the threshold of the applied force of PIP and MCP joints.

3.1 Material and Method

Fig. 3 shows the experimental setup. We mount a vibration motor (FM34F, Inc.) on a six-axis force sensor (BL. Autotech Inc.). To reduce the effect of pressure sensation on force discrimination, participants wore a plastic finger case on their index finger when placing it on the vibration motor.

We investigated the force discrimination threshold by constant method. First, participants straightened their finger on the vibrate motor. Then, they tried to bend their MCP or PIP joint without moving their finger. The six-axis force sensor measured the force applied by the fingertip. When the applied force exceeded the arbitrary force, the vibration motor began to vibrate. Participants repeated this procedure two times. In the first time, the motor vibrated when the applied force exceeded a reference force. In the second time, the motor vibrated when the force exceeded a comparison force. After these two procedures, participants declared which force felt grater, i.e. the comparison force or the reference one or not.

For the grip-type haptic display, the virtual finger must be controlled using a low force range. Therefore, we set two reference forces at 80 and 160 gf, respectively. We set −40.0, −20.0, −10.0, 0, 10.0, 20.0, and 40.0 gf as comparison forces from each reference force. Participants then compared these randomly selected reference and comparison forces. All combinations of reference and comparison forces were selected 20 times. Therefore, through the experiment at a joint, the participants conducted the comparison 280 times in total. This experiment was conducted at PIP and MCP joints. The participants included three adults: two males and one female in their 20's.

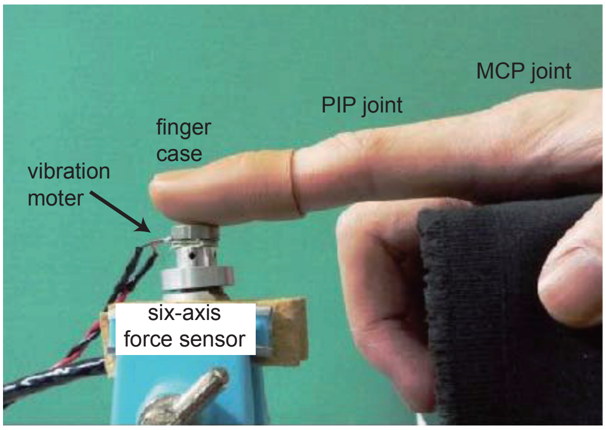

Fig. 3 Experimental setup.

3.2 Results

Fig. 4 and 5 show the results of the experiment. The horizontal axes and vertical axes represent the comparison force and the ratio of responses that considered the comparison force greater than the reference force. The colored points and lines represent the average ratio of the three participants set along a fitting curve. Furthermore, we also summarized the PSE (point of subjective equality) and JND (just noticeable difference) in Tab. 1 and Tab. 2. SD represents the standard deviation. Participants could distinguish increments in the applied force of the PIP and MCP joint that were approximately 11 − 17 gf and 10 − 16 gf, respectively. A two-way (participant, reference force) ANOVA confirmed that neither participant ($F(2, 14)$ = 0.15 for PIP and $F(2, 14)$ = 0.43 for MCP) nor reference force ($F(1, 14)$ = 0.30 for PIP and $F(1, 14)$ = 0.10 for MCP) was a significant factor.

3.2 Discussion

Our results confirm that the user can control the joint-angle positions of a virtual finger through his/her perceived force of each joint. For example, for the joint angle of virtual finger bent 1° by 5 gf, we can perceive a difference in angle of the virtual finger by 2 − 3 °. This value is similar to the angle discrimination threshold of a human's PIP and MCP, which is approximately 1.7 − 2.7 ° [8].Therefore, we confirmed that the user can control the joint-angle position of the virtual finger by means of his/her sense of effort expended to move the finger, without any change in the joint-angle of the finger.

Furthermore, the force discrimination threshold was not depended on the participant and reference force. This result was convenient for us to construct the conversion function in Eq. (3). However, a large force range can cause an undesirable sense of resistance. Therefore, we have to carefully construct the identical control method of the joint position of the finger using a law force range.

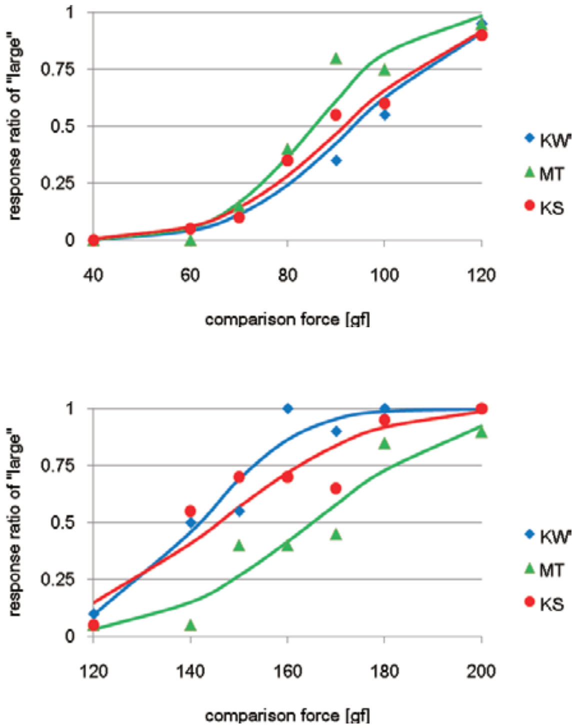

Fig. 4 Results of PIP joint. Above: reference force is 80 gf. Below: reference force is 160 gf.

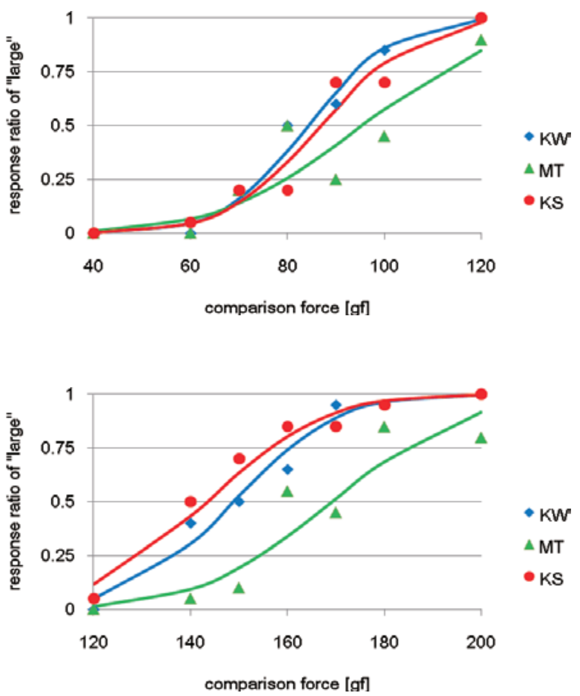

Fig. 5 Results of MCP joint. Above: reference force is 80 gf. Below: reference force is 160 gf.

Table 1 PSE and JND of PIP joint.

	Ref. force	80 [gf]	160 [gf]
KW	PSE	93.7	141.7
	JND (S.D.)	13.3 (4.4)	11.2 (4.1)
MT	PSE	85.5	165.1
	JND (S.D.)	10.8 (4.0)	16.5 (4.9)
KS	PSE	91.7	145.8
	JND (S.D.)	13.8 (4.5)	16.7 (5.0)

Table 2 PSE and JND of MCP joint.

	Ref. force	80 [gf]	160 [gf]
KW	PSE	84.5	148.9
	JND (S.D.)	9.8 (3.8)	11.6 (4.2)
MT	PSE	95.6	169.3
	JND (S.D.)	16.0 (4.9)	15.0 (4.7)
KS	PSE	87.1	143.3
	JND (S.D.)	10.8 (4.0)	13.2 (4.4)

4. HAPTIC FEEDBACK

In the grip-type haptic device, we integrated the spatially distributed tactile feedback with the reactive force to produce dynamically-changing haptic information. We quantitatively evaluated the effectiveness of this haptic feedback using a one-fingered prototype of the grip-type haptic device.

4.1 One-fingered prototype

To construct a one-fingered prototype (Fig. 6), we used the distributed force vector sensor called “GelForce” [9] and an electrotactile display [10].

GelForce can measure the distribution of three-dimensional force vector by an optical method. As the summation of the all force vector, we can calculate a force vector $F = (f_x, f_y, f_z)$ applied by the fingertip. Because the sensor body is made from silicon rubber, it is expected that the sense of resistance is decreased. The resolution of force magnitude is approximately 30 gf and the refresh rate is 60 Hz.

An electrotactile display consists of pin electrodes aligned in rectangular grid of 3 pins × 5 pins. The electric current from each pin electrode activates the nerve fibers in the skin to produce spatially tactile sensation. The magnitude of electric current represents the strength of tactile sensation. Furthermore, it is considered that the electrotactile display can selectively activate the nerve fibers connected to different mechanoreceptors by controlling the pole of the pin electrodes. Therefore, it is expected that the electrotactile display can present various tactile sensation. Another advantage of the electrotactile display is its compact body. Because the display does not need any actuators, it is suitable for integration with the other devices. However, in this prototype, we used anodic stimulation because it can present clear spatially distributed contact information to the user. The pulse width of the electric current was 20 μA and the refresh rate was 60 Hz.

4.2 Virtual hand

To control a virtual hand using the one-fingered prototype and acquire tactile information, we constructed a virtual environment (Fig. 7) using an ODE (Open Dynamics Engine) [11]. The virtual environment consists of a humanoid virtual hand and a target object. The simulation step is 0.01 s.

The user of the one-fingered prototype can control the index finger of the virtual hand and touch the target object. The DoF is 4 for index finger, 2 for MCP joint (bend and side flexion) and 1 for the PIP and DIP (distal Interphalangeal) joints. However, the DIP joint moves in coordination with the PIP joint as Eq. (4) [5].

$$\theta_{DIP} = 0.46\,\theta_{PIP} + 0.083\,\theta_{PIP}^{2} \qquad (4)$$

Therefore, we can approximate the DoF of the index finger to be 3. In this prototype, the joint-angle positions are controlled by forces that can be expressed by the three-dimensional force vector *F* in Eq. (5).

$$\begin{aligned} \theta_{PIP} &= 2kf_z + kf_y \\ \theta_{MCP\_b} &= 2kf_z - kf_y \\ \theta_{MCP\_s} &= kf_x \end{aligned} \qquad (5)$$

In this equation, θ_{MCP_b} and θ_{MCP_s} represent a joint angle of MCP for bending and side flexion, respectively. *k* is a proportionality coefficient from the force to joint angle. These equations are determined by a preliminary experiment to control the PIP and MCP joint independently and intuitively.

To present a spatially distributed tactile sensation using the electrotactile display, we calculate a distribution of pressure applied to the fingertip of virtual hand. The 15 force sensors that are attached to the fingertip of the index finger calculate pressure applied to the fingertip by the target object. This pressure is calculated by a penalty method. The pressure increases proportionate to the distance that the sensor sinks into the object. Furthermore, the pressure also increases in inverse proportionate to the size of the contact area.

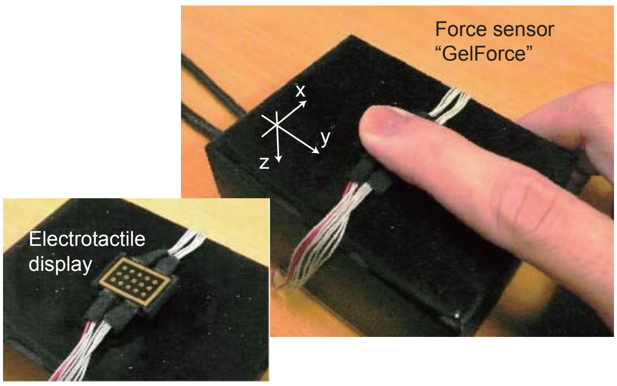

Fig. 6 One-fingered prototype.

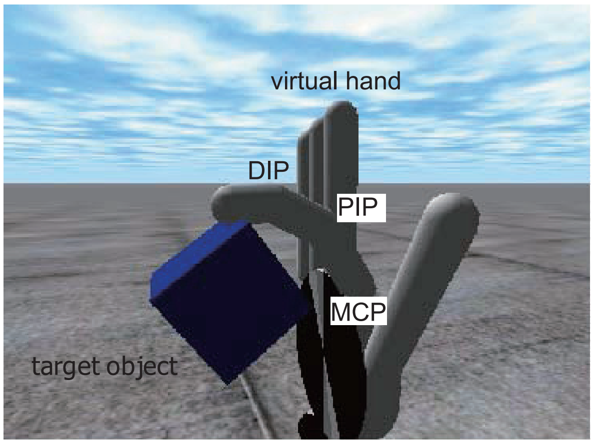

Fig. 7 Virtual hand.

4.3 Active haptic feedback

We qualitatively evaluated the dynamically-changing haptic feedback provided by the electro tactile display.

For evaluation, we used two laptop PCs: one PC was used to control the one-fingered prototype, and the other PC was used to simulate a virtual environment. Both the PCs were connected by a LAN, and the data of force vector and pressure distribution was sent by 100 Hz using UDP protocol. For the target object, we constructed a box that rotated at a constant speed. Both the speed and the direction of rotation could be arbitrarily changed. From the dynamically-changing electrotactile stimulus, the users could feel the rotation of the box when the virtual finger touched it, even without moving the virtual finger. Furthermore, they could also feel that their finger was being pushed up by the box.

Approximately 30 adults (whose ages ranged from the 20’s to 40’s) experienced this system. The participants tried to control the virtual finger based on the force applied from their index finger to the device. They could control each joint of the virtual finger independently and intuitively. Furthermore, most of them could perceive haptic sensation that was dynamically-changing. They could perceive the difference of edge and surface, contact position, and rotation of the box. Therefore, we concluded that the proposed grip-type haptic display can produce active haptic feedback without the need for actuators to produce reactive force. As a next step, we will quantitatively investigate how this dynamically-changing haptic sensation can be best produced.

It must be noted that many participants pointed out that the electric sensation decreased their realistic haptic sensation. This electric sensation is the greatest problem of the electrotactile display. We have to decrease the electric sensation to produce a more realistic sensation of touch.

5. CONCLUSION

In this study, we proposed a grip-type haptic display that uses the user’s grasping force and spatially distributed tactile feedback to control a virtual finger and produce haptic sensation. To control the virtual finger, the user has to recognize his/her finger position the basis of his/her sense of effort expended. Therefore, it is important to discriminate the force applied by the finger. We evaluated the threshold at which force could be distinguished and confirmed that the threshold was sufficient for controlling the angle position of a virtual finger. Furthermore, we constructed a one-fingered prototype using an electrotactile display. Using this prototype, we qualitatively evaluated the effectiveness of the haptic feedback that integrates both the spatially distributed tactile feedback and reactive force.

In future, we intend to quantitatively evaluate the effectiveness of the haptic feedback of the proposed device. We expect that the spatially distributed tactile feedback and the reactive force can present the physical properties of an object, such as stiffness, size, and shape. Furthermore, we also intend to implement a multi-fingered grip-type haptic display by integrating MeisterGRIP with the electrotactile display.

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