Development of a Wearable Haptic Device that Presents the Haptic Sensation Corresponding to Three Fingers on the Forearm

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ABSTRACT

Numerous methods have been proposed for presenting tactile sensations from objects in virtual environments. In particular, wearable tactile displays for the fingers, such as fingertip-type and glove-type displays, have been intensely studied. However, the weight and size of these devices typically hinder the free movement of the fingers, especially in a multi-finger scenario. To cope with this issue, we have proposed a method of presenting the haptic sensation of the fingertip to the forearm, including the direction of force. In this study, we extended the method to three fingertips (thumb, index finger and middle finger) and three locations on the forearm using a five-bar linkage mechanism. We tested whether all of the tactile information presented by the device could be discriminated, and confirmed that the discrimination ability was about 90%. Then we conducted an experiment to present the grasping force in a virtual environment, confirming that the realism of the experience was improved by our device, compared with the conditions with no haptic or with vibration cues.

KEYWORDS

Haptic; Haptic Devices; Five bar linkage mechanism; Virtual Reality

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1 INTRODUCTION

Many studies have attempted to present tactile information in virtual reality (VR). The fingers are the main targets of haptic presentation in VR, because we manipulate objects with our fingers and they are embedded with densely populated receptors that are sensitive to texture, shape, and weight [1].

Many wearable tactile displays for the fingers, such as fingertip and glove-type displays, have been proposed for presenting information on the strength and direction of a force to the fingers. However, the size of most of these devices hinders free movement, especially when a device with multiple degrees of-freedom (DoF) is attached to the fingertips in a multi-finger scenario.

To tackle this issue, Moriyama et al. have proposed a method of presenting the strength and direction of a force that is normally presented to the fingertip to another part of the body [2]. At this initial trial, they found that the dorsal part of the wrist was an appropriate location corresponding to the index finger. They also made a device that presents the strength and direction of a force on the thumb and index finger to another part of the body, and conducted a preliminary user study in VR, confirming that pressure sensation generated by our device gives more natural sensation than vibration.

In this paper, we present a follow-up study in which we extend the method to a three-fingers case. A minimum of three fingers is needed to firmly grip or manipulate an object, and therefore it can be adopted in numerous situations including teleoperation (Figure 1.a). This study consists of two experiments. In the first one, we verified that the tactile information presented by the device could be discriminated (pressure and right/left tangential force). In the second one we examined the multi-finger case, taking grasping by the thumb, index finger and middle finger, to confirm that certain realism can be achieved using our method.

2 RELATED WORK

Numerous studies have examined the presentation of haptic information directly to the hand or fingertip when touching an object in VR.

The first type of wearable haptic device presents a force to the fingertip [3-5]. However, presenting tactile sensation to multiple fingers makes the devices large and difficult to wear and take off. Presenting multiple DoF for each finger is also difficult.

The second type of wearable haptic device attaches directly to the fingertips, and presents force information by causing deformation of the skin on the fingertips. Although skin deformation provides sufficient cues to represent such a force [6-9], when presenting a force with multiple DoF, including the direction of force to the fingertip, the weight of the apparatus becomes a heavy burden on the user, and interference between the devices cannot be avoided.

One practical solution to these problems is to present the haptic information to other parts of the body rather than the fingertip. This is a common method in the study of sensory prosthetic hands, many of which use transducers placed on the arms and shoulders [10-13]. However, these devices do not present information on the direction of force.

The presentation of force by stretching the skin on the forearm has been studied. For example, stretching the skin in a rotational [14,15] or translational direction [16-18] has been considered as a method of presenting the sense of force. More recently, Casini realized a two-DoF pressure and skin-stretch device for the forearm [19]. While the concept of presenting force information to the forearm is similar to our work, to the best of our knowledge, the multi-finger scenario has not been fully explored.

There is extensive discussion in the robotics field regarding the minimum number of fingers required for manipulation. From the perspective of cost and manipulation potential, robots are typically developed with three fingers, which is sufficient to conduct dexterous tasks [20-23].

Based on this knowledge of robotics, we propose to feed back the haptic sensation of the thumb, index finger, and middle finger to different areas of the forearm using a wearable device. Presenting the information to another part of the body without attaching a device directly to the finger or hand leaves the fingers with total freedom of movement.

3 DEVICE DESIGN

The device adopts an M-shaped structure five-bar linkage mechanism (Figure 1.a). Tsetserukou proposed this as a link mechanism for presenting the sensation of force to the fingertip [24] or to the palm [25]. Based on these previous studies, we created a device that can be worn on the forearm by using the Velcro tape. Two-DoF movement can be achieved by controlling two servomotors (Umemoto LLC Tower Pro SG 90 Digital Micro Servo). The parts that present the haptic sensation can move up and down, left and right. An adhesive gel seal (Vitrode F, Nihon Kohden Co., Ltd.) is attached to the skin where the tactile sense is presented. By connecting the tip of the device to the protrusion on the adhesive gel sheet, pressure sensation can be presented by the up and down movement and tangential friction sensation can be presented by the left and right movement (Figure 1.b).

The whole device is composed of two five-bar linkage mechanisms on the dorsal side of the forearm, separated by 100 mm, representing the index and middle fingers, and one five-bar linkage mechanism on the volar side of the forearm, representing the thumb. Separation is well above the two-point discrimination threshold of forearm skin, which is around 40 mm [26].

Moriyama et al. [2] reported that they chose four candidate locations for the haptic presentation of the index finger: the dorsal and volar side of the forearm close to the wrist, and the dorsal and volar side of the forearm on the elbow side. The results showed that the dorsal side of the forearm close to the wrist was the best location to present haptic sensation to the index finger. Our current prototype is based on this result: the dorsal side of the forearm close to the wrist relates to the index finger, the dorsal side away from the wrist relates to the middle finger, and the volar side relates to the thumb.

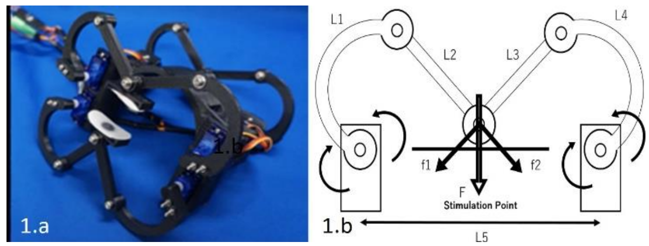

Figure 1: Device from top view (1.a); Device design (1.b)

Table 1: Device Specification

Link Length L1, L2, L3, L4 [mm]	50
Link Length L5 [mm]	180
Pushing Force F [N]	6.0
Tangential Friction Force f1, f2 [N]	1.2

4 EXPERIMENT 1: DISCRIMINATION OF THE TACTILE INFORMATION BY THE DEVICE

4.1 Experimental Conditions

We confirmed that the haptic information presented by the device could be discriminated. First, we examined the case when the force was presented to different locations in the vertical direction, simulating the sense of pressure (pressure condition). Second, we examined the case with all tactile information (pressure and right/left tangential direction) presented to two different positions on the forearm (mixed condition).

In the pressure condition, all three places corresponding to the thumb, index finger, and middle finger were used (Figure 2.a). We tested whether each one of the stimulus from two pairs {index finger, middle finger}, {middle finger, thumb}, {thumb, index finger} could be discriminated. In the mixed condition, we limited the presentation to two locations on the dorsal side, to shorten the experiment. These two points corresponded to the index finger and middle finger (Figure 2.b). For example, it was confirmed whether pairs such as {pressure sensation of the index finger, leftward tangential shift of the middle finger}, {leftward tangential shift of the index finger, rightward tangential shift of the index finger} could be discriminated.

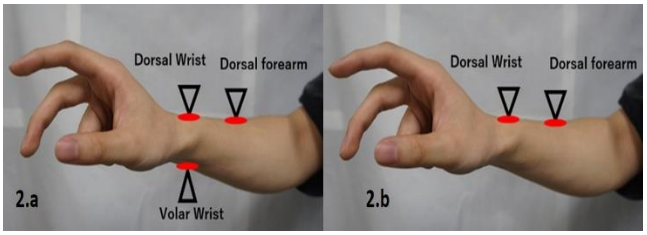

Figure 2: Stimulation points for pressure condition (2.a); Stimulation points for mixed condition (2.b)

Using stimulus pairs A and B, the following procedure was used to examine discrimination ability.

1. A was presented for 1 second, followed by 1 second rest.
2. B was presented for 1 second, followed by 2 seconds rest.
3. A or B was presented randomly, and participants were asked whether the last stimulus was A or B.

Ten trials were conducted for each of the three combinations, 5 in the order A-B and 5 in the order B-A, making a total of 30 trials presented in random order.

In the mixed condition, vertical or tangential (left and right) direction was presented to the index finger and the middle finger. Two fingers and three directions of force gave six conditions, and extracting pairs from these conditions gave 15 combination pairs. Each combination was tested ten times (A-B 5 times, B-A 5 times), resulting in a total of 150 trials. All trials were conducted in random order. We recruited ten participants (six females and four males, aged 21 to 34). During the experiment, the device was attached and the participant's sight was blocked using an eye mask. White noise was played through headphones to mask the noise of the servomotor.

4.3 Results of Experiment 1

4.3.1 Presentation of pressure sensation to all finger combinations.

The number of correct responses for the pressure condition is shown in Figure 3. The results indicate that the participants were able to identify where the pressure sense was presented with a probability of 89% or more.

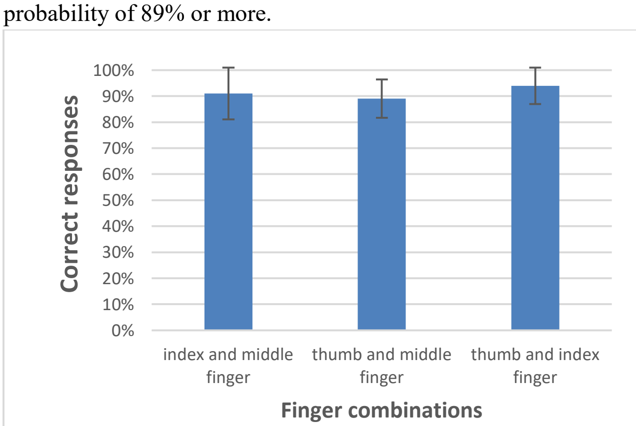

Figure 3: Identification of the sense of pressure in three-finger combinations

4.3.2 Presentation of pressure sensation or the tangential sensation to the index finger and middle finger.

Table 2 shows the correct response rate for the mixed pressure and tangential sensation condition, presented in different combinations corresponding to the index and middle fingers.

Table 2: Discrimination between pressure and tangential friction in two-finger combinations

	Index finger (Left friction)	Index finger (Right friction)	Middle finger (Pressure force)	Middle finger (Left friction)	Middle finger (Right friction)
Index finger (Pressure force)	95%±4.2%	95%±6.1%	93%±5.4%	98%±4.5%	99%±2.1%
Index finger (Left friction)		88%±6.9%	94%±8.6%	94%±6.6%	95%±6.9%
Index finger (Right friction)			96%±5.6%	97%±4.7%	95%±5.3%
Middle finger (Pressure force)				97%±3.5%	95%±5.5%
Middle finger (Left friction)					96%±4.7%

4.4 Discussion

Very high discrimination rates were obtained under both the pressure condition and the mixed condition, which suggests the device can independently present all types of tactile information.

6 EXPERIMENT 2 : GRASPING AN OBJECT WITH THREE FINGERS

6.1 Outline

We considered the grasping and lifting of an object as a task involving multiple fingers and multiple directions of force. When grasping an object, the object exerts vertical pressure on the fingers. When lifting the grasped object, the force of gravity results in lateral skin deformation. Presenting the force information to the wrist, including the direction perceived by the fingertip, may lead to a more realistic experience.

Moriyama et al. conducted experiments using only the tactile sense corresponding to the index finger and thumb [2]. In this experiment, using the newly developed device, we presented to the forearm the haptic information (i.e, the pressure sensation and tangential friction force) that should be perceived by the index finger, middle finger, and thumb when holding a virtual object. We examined whether realism in this case was better than in the case with no haptic presentation and in the case where the tactile presentation was provided by vibrators. The vibrator used in this experiment was a linear resonant actuator (Nihondensan Copal Corporation, LD 14-002), which vibrates at 150 Hz. The vibrators were incorporated inside the thumb, index finger, and middle finger of the glove.

6.2 Experimental Conditions

An Oculus Rift was used as an HMD for the stimulation point visual presentation. LeapMotion was used for finger tracking. A virtual 3D scene was rendered using the Unity3D engine. The following four conditions were prepared for the tactile presentation. In all conditions, the participants wore the prepared device and a glove that incorporated the vibrators.

1. No haptic presentation.

2. The vibrators presented vibration to the fingers when the fingers were in contact with the object.

3. Pressure sensation was presented to the three locations when the fingers grasped the object.

4. Pressure sensation was presented to the three locations when the fingers grasped the object, and a tangential force was presented to the three locations when lifting the object.

Under condition 1, the virtual object was gripped and lifted with no tactile sensation. Under condition 2, the vibrators were continuously driven when the object was being gripped. Under condition 3, a force was applied in the direction of pressing the forearm from upper and bottom side (both sides) when the user gripped the object in VR environment. Condition 4 reproduced the same force applied in condition 3 when grasping the cup and the skin deformation on the finger when actually grasping and lifting the object by presenting a tangential friction force simultaneously to the forearm.

The case without haptic presentation was taken as the standard condition, and the four conditions were then presented randomly. The participants were asked to score the subjective realism using a 7-point Likert scale (7: realism was much greater than that for the standard stimulus, 1: realism was much less than that for the standard stimulus). We recruited eight participants, four females and four males aged 21 to 24.

6.3 Experiment Environment

A desk and a metal cup were displayed in the VR scene. Participants were asked to hold the cup with their middle finger, index finger, and thumb, lift the cup, and return it to the desk five times. The participants were first asked to raise the cup five times without haptic presentation (standard condition).

6.4 Results

Figure 4 shows the results of the experiment 2.

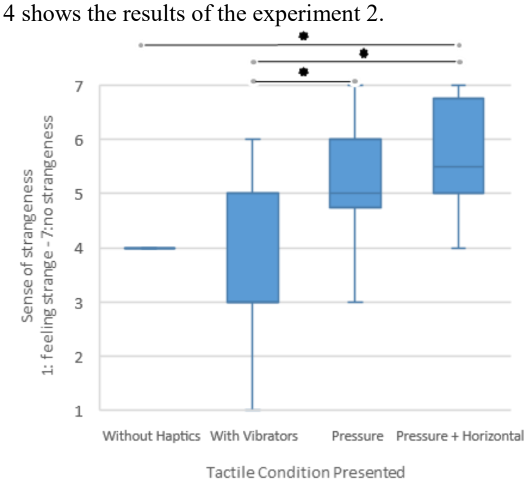

Figure 4: Realism under four conditions

Friedman's nonparametric test showed a significant difference between the tactile presentation condition, and the combined pressure sense and tangential friction force condition ($p < 0.05$). Furthermore, significant differences were observed between the vibrator condition and the pressure only condition, and the combined pressure and tangential friction force condition ($p < 0.05$).

6.5 Discussion

Comparing the vibration and force conditions, the realism was greatly improved when haptic sensation was presented by the device.

Although the difference was not significant, scores for the combined pressure and tangential friction force condition tended to be higher than for the pressure only condition. In a study by Moriyama et al. using two fingers, the pressure only condition scored higher than the combined pressure and tangential force condition [2]. We believe that this difference was caused by increasing the number of fingers in this experiment, and the sense of discomfort between pressure and tangential friction force was reduced by finely adjusting the timing and strength of the presentation. When presenting combined pressure and tangential force, one participant commented that "the feeling seems to be a vertical force applied to wrist rather than the sense of skin tangential deformation." This comment suggests that skin deformation is an important cue for perceiving force, even if it is presented to the forearm. There were several observations that weight can be rendered by force presentation in the shear direction to the forearm [27], and our current study showed that realism in the VR environment can be improved by this rendering approach.

7 CONCLUSION

We proposed a method for presenting haptic information generated at the fingertip to the other parts of the body, in a three-finger scenario (thumb, index finger, middle finger). Examination of the location and direction of presentation showed that even when different tactile information was presented to each area, it could be sufficiently discriminated. In addition, the results suggest that the use of this device can lead to an improvement in the realism of the experience of gripping and lifting an object in a VR environment.

Since the device currently has only two DoF, we could only present the sensations of pressure and tangential friction. We will improve the device by adding a third DoF to present various sensations, as well as applying it to a two-handed situation.

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