Development of a Wearable Haptic Device That Presents Haptics Sensation of the Finger Pad to the Forearm*

Taha K. Moriyama, Ayaka Nishi, Rei Sakuragi, Takuto Nakamura, Hiroyuki Kajimoto

***Abstract*—While many wearable tactile displays for the fingers, such as fingertip-type and glove-type displays, have been developed, their weight and size typically hinder the free movement of fingers, especially when considering the multi-finger scenario. We propose a method of presenting the haptics sensation of the fingertip on the forearm, not on the fingertip, to address this issue. A five-bar linkage mechanism was adopted to present a two-degree-of-freedom force. We conducted two experiments. In the first experiment, we presented a pressure sensation and a horizontal friction sensation perceived by the index finger to multiple sites of the forearm to search for a proper location of presentation, finding that the volar part of the wrist is optimal. On the basis of this result, we developed a device for the index finger and thumb, and conducted a second experiment to present the grasping force in a virtual reality environment. The realism of the experience in virtual reality was better when using the designed device than for no haptics cue or for vibration conditions.**

I. INTRODUCTION

Virtual reality (VR) has recently become popular partly owing to the availability of inexpensive head-mounted displays (HMDs), which put the spotlight on haptics presentation to reproduce rich experiences in VR. The main targets of haptics presentation in VR are the fingers, because we manipulate objects with our fingers and our fingers are embedded with many receptors that are sensitive to texture, shape and weight [1].

Among many sensory channels of the fingertips, particularly important channels are those of the strength and direction of a force, which are indispensable information when manipulating an object. While other senses, such as the senses of vibration and temperature, are important in identifying a grasped object and sometimes necessary in manipulation (e.g., the estimation of the frictional coefficient), considering that it is possible for people to carry out daily tasks even when wearing gloves, their significance give a step back to the senses of the strength and direction of a force.

Many devices have been proposed for presenting the strength and direction information of a force to the fingers. Typically, a multi-degree-of-freedom (DoF) device is attached to a fingertip, which hinders the free movement of fingers, especially in the multi-finger scenario.

To tackle this issue, we propose a method of presenting the strength and direction of a force normally given to the fingertip to another part (wrist/forearm) of the body (Figure 1). A M-shaped five-bar linkage mechanism, which was first proposed as a link mechanism for force sense presentation to the fingertip by Tsetserukou [20], is adopted to present a two-DoF force.

The present paper makes two contributions. One contribution is that we find the optimal location of the forearm/wrist at which to present a force to the index finger. The other contribution is that we examine the multi-finger case, taking grasping by the index finger and thumb as an example, to confirm that certain realism can be achieved using our method.

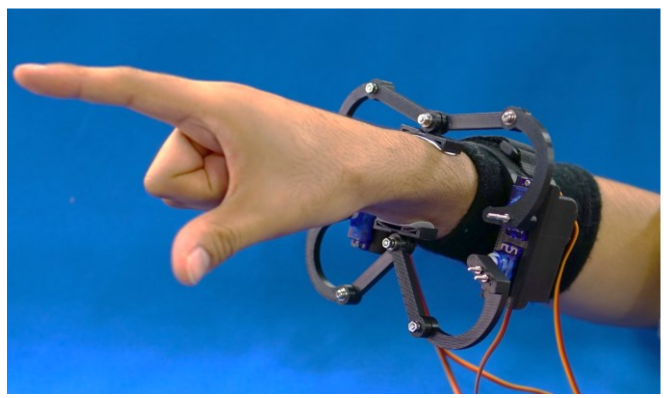

Figure 1: Device for haptics presentation to two fingers

II. RELATED WORK

Numerous studies have presented haptics information directly to the hands and fingertips for the VR environment. Here we outline haptics devices that are wearable; i.e., the whole mechanism can be mounted on the palm or finger and presents not only vibrations but also a sense of force.

The first group of wearable haptics devices presents a force to the fingertip, using a device mounted on the wrist or the back of the hand [1][3][4]. Because these have a base point at a location away from the fingertip, it is possible to present the actual force to bending fingers. However, most of these devices are large and difficult to wear or to take off. Multi-DoF presentation is also difficult.

The second group of wearable haptics device is attached to the fingertip and deforms the skin. While it is impossible to generate an actual force like a force bending the finger against the fingertip, skin deformation gives sufficient cues for a force [5] [6] [7]. While some devices present a multiple-DoF force sensation to the fingertips, they are too heavy and large,

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especially for a multi-DoF mechanism. Attaching the devices to multiple fingers give rise to physical interference between devices.

One realistic solution to the above issues is to present the haptics information of the fingertip to other parts of the body [9]. This is a common method used in the study of tactile sensory prosthetic hands, and there have been many attempts to place vibrators on the arms and shoulders to present sensations for prosthetic hands [9][11]. This approach has also been taken for VR. The tactile sensation of palms, for example, was mapped to soles using a pneumatically driven device [12], and a ring-shaped device presented finger tactile signals to the wrist [13]. However, most of such attempts presented only a vibratory or pressure sensation, and the direction of the force was not presented. Furthermore, the achieved realism was not fully evaluated.

The presentation of a force or skin stretch to the forearm has been intensely studied. For example, as a method of presenting a force sensation, skin stretch in a rotational [14][15] or translational direction [16][17][18] has been considered. More recently, Casini realized a two-DoF pressure and skin-stretch device for the forearm [19]. However, although the concept of presenting force information to the forearm and freeing the fingertip is similar, to the best of our knowledge, the multi-finger scenario has not been fully explored.

In this paper, we propose to feedback the haptics sensation perceived at the fingertip to the wrist or forearm when the user touches an object in VR. By presenting the information to other parts of the body without attaching a device to the finger or hand directly, the fingers are totally free to move.

III. Device Design

A. Design Overview

Figure 2 shows the appearance of a device for haptics presentation to one finger. The device comprises a base with a large area that is fixed to the arm with Velcro tape, a five-bar linkage driven by two radio-controlled servomotors (Umemoto LLC Tower Pro SG 90 Digital Micro Servo), and an adhesive gel seal (Vitrode F, manufactured by Nihon Kohden Co., Ltd.) that connects the skin to the middle point of the five-bar link. The system is capable of presenting upward, downward, leftward and rightward forces. The device weighs about 100 g.

Figure 2: Device for haptics presentation to one finger

B. Five-Bar Linkage Mechanism

The device adopts a five-bar linkage mechanism. Unlike the usual five-bar linkage mechanism, it adopts an M-shaped structure, which was first proposed as a link mechanism for force sense presentation to the fingertip by Tsetserukou [20]. Following the cited study, we created a device that can be worn on the wrist or forearm. By controlling two servomotors at the base, we realized the presentation of a two-DoF force, with one DoF for pressure and the other DoF for lateral skin stretch. The maximum force in the downward direction is 6.0 N and the maximum demonstrating force in the lateral direction is 1.2 N (table 1).

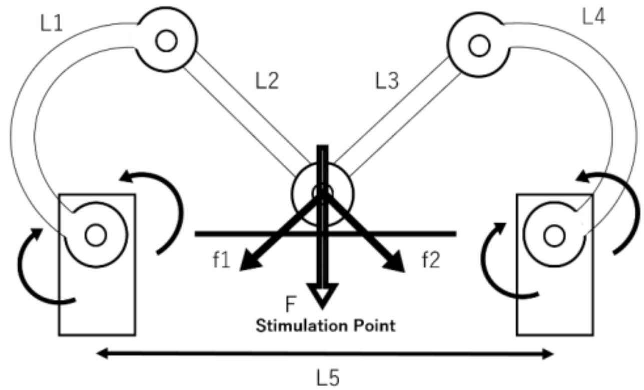

Figure 3: Five-bar linkage mechanism

TABLE I. Device Specifications

Servo Motor	**Tower Pro SG90**
Link Length L_1, L_2, L_3, L_4 [mm]	**50**
Link Length L_5 [mm]	**180**
Weight [g]	**100**
Pushing Force F [N]	**6.0**
Horizontal Friction Force f_1, f_2 [N]	**1.2**

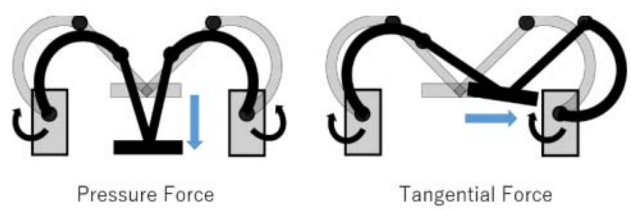

Figure 4: Operation of the Device

IV. Experiment 1: Presentation of the Force Haptic Sensation to One Finger

The first experiment investigated the proper location of haptics sense presentation to the index finger. Users were instructed to move their arms in the VR environment and make contact with the object, while the device presented the pressure or tangential force.

A. Experimental Conditions

Dorsal parts of the wrist and forearm, which were on a straight line from the index finger, and volar parts that were on the opposite side, were selected as candidate locations for the haptics sense presentation to the index finger (Fig. 5). The distance D between the wrist and forearm was 120 mm. For visual presentation, an Oculus Rift (https://www.oculus.com/rift/) was used as an HMD. LeapMotion (https://www.leapmotion.com/) was used for finger tracking. A virtual three-dimensional (3D) scene was rendered using the Unity3D engine (https://unity3d.com/jp). A desk was displayed in front of the participants, and the participants were requested to move their arms vertically or horizontally.

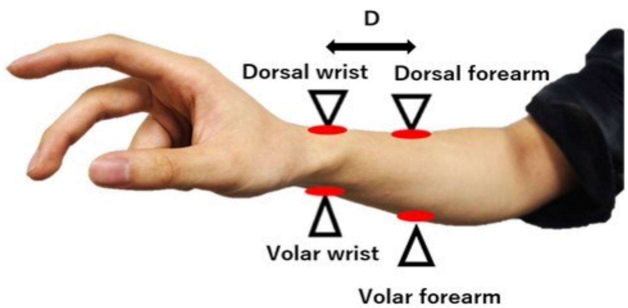

Figure 5: Presenting parts of the haptics sense of the fingertip

Three conditions of relationships between finger motion and haptics presentation were prepared.

1. Vertical motion and its associated pressure sense
2. Tangential motion and its associated lateral skin stretch in the same direction as the movement
3. Tangential motion and its associated lateral skin stretch in the direction opposite the movement

For condition 1, a red marker 40 cm above the desk moved downward to the surface of the desk in 4 seconds. A virtual hand, representing the user's real hand, was displayed and measured by LeapMotion. Participants were asked to match the hand movement to the marker as best as possible. When the marker touched the desk, a pressure force was applied perpendicular to the skin. One trial comprised 10 repetitions.

For conditions 2 and 3, the marker was on the desk, moving left and right over 10 cm, taking 1 second for one loop. Again, the participants were asked to match the hand movement to the marker as best as possible. Haptics presentation to the skin at this time was in the same direction as the marker motion for condition 2 (i.e., the skin was pulled to the right when the marker moved to the right), while presentation was opposite to the movement of the marker for condition 3. One trial comprised seven repetitions.

First, an experiment with the pressure sense of condition 1 was performed. The participants were asked to follow the red marker. Four stimulation locations were randomly selected and the experiment was conducted once for each location, giving four trials in total.

We next randomly selected one of conditions 2 and 3. Again participants were asked to follow the red marker. Four trials for the four locations were then carried out in random order. Finally, the remaining condition 2 or 3 was selected and four trials for the four locations were conducted in random order.

In each trial, participants were asked to give the sense of strangeness (unnatural feeling) associated with the presented haptics sensation on a seven-level Likert scale of 1 (feeling strange) to 7 (no strangeness). Our intention was to measure the subjective feeling of naturalness of the device, but because a "natural" feeling when presenting the fingertip sensation to another location might be difficult to interpret, we used the term "sense of strangeness". We also note that the Japanese term that we used here (i.e., "iwakan") also includes a sense of discomfort and a sense of deviation from the natural state.

We recruited 11 participants (four females and seven males, 21 to 24 years old) for condition 1 and nine participants (four females and five males, 21 to 24 years old) for conditions 2 and 3.

Figure 6: Experimental situation

B. *Results of Experiment 1*

Figure 7 is a graph showing the score of the sense of strangeness when vertical pressure associated with vertical motion was applied. A nonparametric analysis of variance (Friedman method) was conducted, and a significant difference was found at the 5% level between the dorsal part of the wrist and the volar part of the wrist ($p < 0.05$). This result indicates that the dorsal part of the wrist is the best location among the four candidate locations when presenting a pressure sense to the index finger.

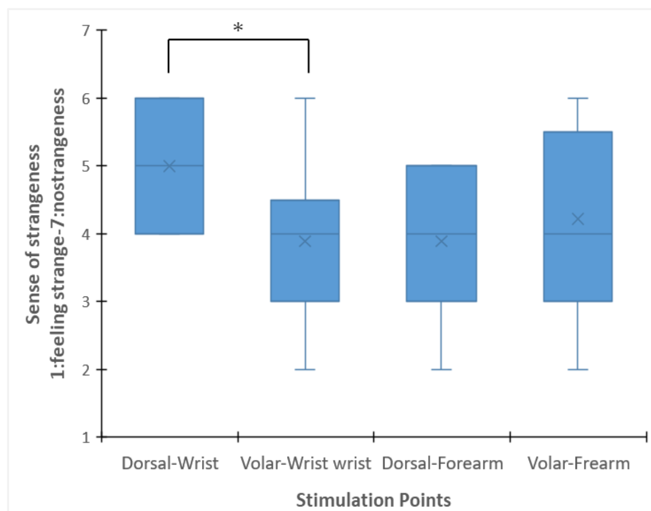

Figure 7: Sense of strangeness when presenting a pressure sensation

Figure 8 and 9 present scores of the strangeness feeling for the tangential force presentation. Figure 8 presents results for condition 2 (where the direction of skin lateral deformation was the same as that of hand movement) while Figure 9 presents results for condition 3.

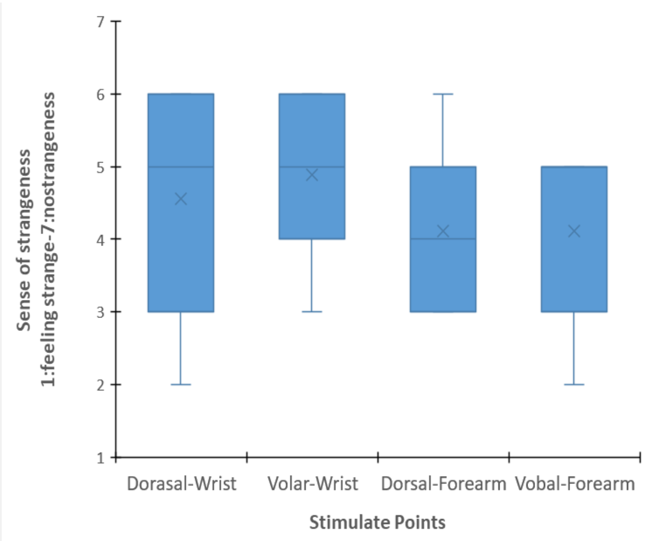

Figure 8: Sense of strangeness when presenting a horizontal friction force in the same direction as the movement

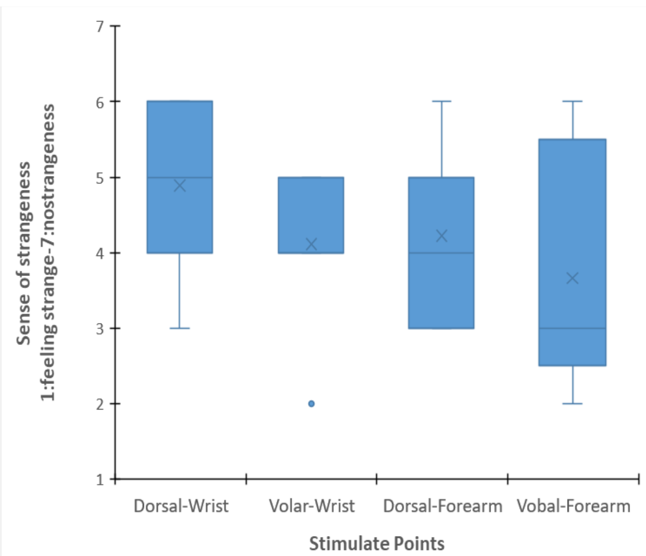

Figure 9: Sense of strangeness when presenting a horizontal friction force in the direction opposite the movement

A nonparametric variance analysis (Friedman method) confirmed that there was no significant difference between any pairs of the stimulation location, although the wrist seems better than the forearm. Furthermore, the trends were similar for the two conditions, indicating that neither the location of stimulation nor the direction of skin stretch plays a significant role in determining the sense of strangeness for tangential skin deformation.

C. *Discussion on Experiment 1*

According to the result of pressure sensation associated with vertical hand motion, the use of the volar part of the wrist was the least uncomfortable when presenting the pressure sense of the fingertip of the index finger in the VR environment. Considering that the force applied to the finger from the object is upward and the direction of the force pressing the volar part of the skin is downward, the direction of force is reversed. However, because the direction of the force applied by the finger to the target is the same as the direction of the force presented from the device, we consider the possibility that the participant interpreted the device as her/his finger.

According to the result of tangential force sensation associated with horizontal hand motion, no difference was observed in the case that a horizontal friction force was presented in the same direction as the hand motion and in the case that the force was presented in the opposite direction. In addition, six of the nine participants commented that they did not notice a difference between conditions 2 and 3. This reminds us of the phenomenon discovered by Shibahara [21] that the direction of a tangential force does not contribute much to realism with regard to tangential hand movement. Furthermore, differences among locations of stimulation were small.

The above results reveal that the volar part of the wrist is the most appropriate location among the four candidates for presenting pressure and a horizontal friction force of the index finger. That is to say, it is possible to realize a configuration capable of presenting two kinds of tactile information of the vertical pressure feeling and horizontal friction force feeling of the index finger with one device on the wrist.

V. Experiment 2: Grasping an Object With Two Fingers

To evaluate the multi-finger, multi-DoF situation, we consider a task of grasping an object with the thumb and index finger. When grasping an object, vertical pressure from the object is applied to the fingers. When lifting the grasped object, the gravity force results in lateral skin deformation. Reproducing the force information to the wrist including the direction perceived by the fingertip may lead to a more realistic experience.

We redesigned the device as shown in Figure **1**. Compared with the device used in Experiment 1, another five-bar linkage mechanism was added to the dorsal side of the wrist. According to the results of Experiment 1, the volar-part mechanism corresponded to the haptics sense of the index finger. The optimal location of haptics presentation corresponding to the thumb has not yet been examined, but we associated the dorsal-part mechanism with the thumb.

Using this device, we presented haptics information (i.e., the pressure sensation and horizontal friction force) that should be perceived by the index finger and thumb when holding a virtual object, on the wrist. We examined whether realism was better than that in the case that there is no haptics presentation and that in the case that the tactile presentation is provided with vibrators. The vibrator used this time was a linear resonant actuator (Nihondensan Copal Corporation, LD 14-002), which vibrates at 150 Hz. We installed a total of four vibrators, two on the volar part and two on the dorsal part of the base of the device.

A. *Experimental Conditions*

As in Experiment 1, an Oculus Rift was used as the HMD, fingers were tracked using LeapMotion, and Unity was used in rendering the 3D environment.

The following five conditions were prepared for haptics presentation. Participants wore the same device under all conditions.

1. There was no haptics presentation.

2. Vibration was presented by vibrators only at the moment of contact.

3. Vibration was presented by vibrators when fingers grasped the object.

4. A pressure sensation was presented to two locations when fingers grasped the object.

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

Under condition 1, the virtual object was gripped and lifted with no tactile sense presentation. Both conditions 2 and 3 used vibrators. Under condition 2, the vibrators were driven for 0.5 seconds only when both fingers touched the object, while the vibrators were continuously driven when the object was being gripped under condition 3.

Under condition 4, a force was applied in the direction of pressing the skin from both sides when the user gripped the object in VR. Condition 5 reproduces the skin deformation on the finger when actually grasping an object by presenting a tangential friction force simultaneously to the wrist when grasping the object.

In the experiment, the case without haptics presentation was taken as a standard stimulus, and the five conditions were then presented randomly. The participants were asked to score the subjective realism using seven levels of the 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 11 participants, comprising four females and seven males, aged 21 to 24 years.

B. Experimental Environment

A desk and iron cup were displayed in the VR scene. Participants were asked to hold the cup with an index finger and thumb, and lift the cup and return it to the desk five times. The participants were first asked to raise the cup five times without haptics presentation (standard stimulus). The five conditions were then presented in random order.

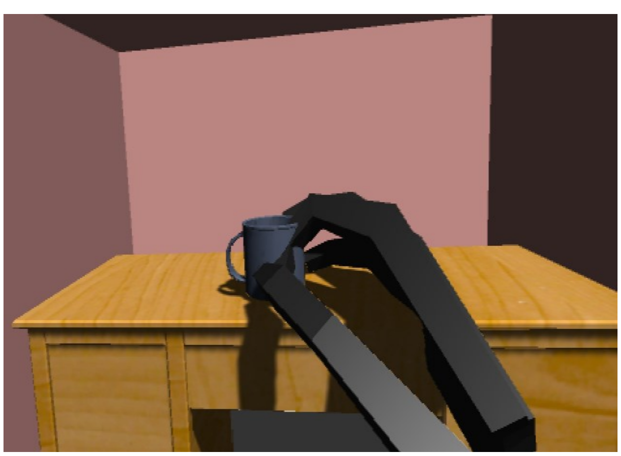

Figure 10: Image presented by the HMD in the experiment

C. Results of Experiment 2

Figure 11 shows the results of the experiment.

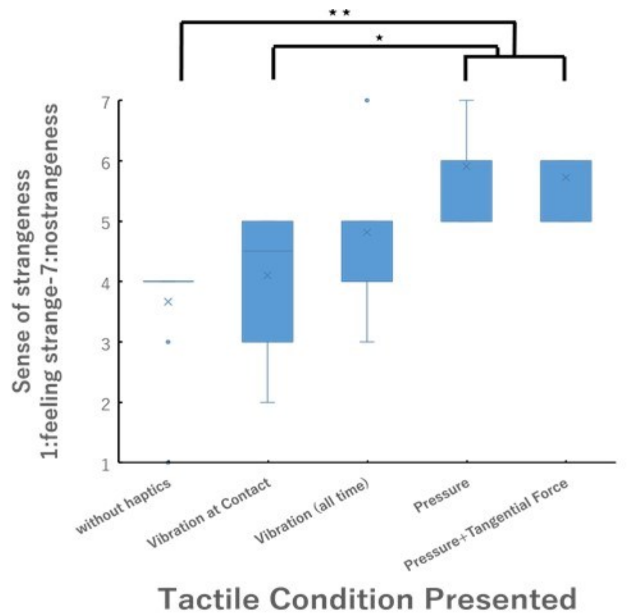

Figure11: Evaluation of the improvement in realism under five conditions

Nonparametric variance analysis (Friedman method) revealed significant differences between conditions 1 and 4 (without haptics condition and pressure sensation presented condition, $p < 0.005$), conditions 1 and 5 (without haptics condition and pressure with tangential force presented condition, $p < 0.005$), conditions 2 and 4 (vibration presented at the moment of contact and pressure sensation presented condition, $p < 0.05$), and conditions 2 and 5 (vibration presented at the moment of contact and pressure with tangential force presented condition, $p < 0.05$).

D. Discussion on Experiment 2

Comparing the case with vibration and a force, the realism was greatly improved when haptics were presented by the created device. The participants commented "The feeling was close to the fingertips" and "I clearly felt a sense of grasping an object, not just cognition of touching or grasping an object, even if the touch was not on the fingertips". These comments suggest that we can improve realism by presenting a force applied to the fingertip on the wrist.

There was no significant difference between the case that the pressure sensation was presented only (condition 4) and the case that pressure and tangential deformation were presented (condition 5). Considering that the median score of condition 4 was 6, the score might have saturated this time. In addition, owing to the five-bar linkage mechanism, the ratio of the pressing force and the tangential force depends on the thickness of the arm, which might have resulted in an inappropriately strong or weak tangential force for some participants. Furthermore, we obtained comments from some participants that an instantaneous force was perceived twice for condition 5, which was a somewhat uncomfortable feeling. This is probably due to the difficulty in changing the force smoothly owing to the characteristics of the radio-controlled servomotor currently in use, and the situation should be improved using a DC motor that can present a smoother force translation.

Meanwhile, there was a comment that the tangential force felt more like a vertical weight rather than a lateral skin stretch. This comment suggests that it is meaningful to present a directional force to the wrist.

VI. Conclusion

We proposed the presentation of haptics information generated at the fingertip to other parts of the body, considering a multi-finger, multi-DoF scenario. The first experiment showed that the volar part of the wrist can present the haptics sensation of the index finger with the least strangeness. The second experiment showed that the realism of the grasping experience was improved by our device.

We cannot show a significant contribution of the tangential force to subjective realism at this time, partly owing to the limitations of the actuators. We will improve the device by adopting a high-response DC motor and consider a mechanism with more DoFs, and involve more fingers.

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References

[1] E. R. Kandel, J. H. Schwartz, and T. M. Jessell, *Principles of Neural Science*, Fourth Edition, A Division of The McGraw-Hill Companies, 2000.

[2] CybaerGloveSystems, http://www.cyberglovesystems.com/sybergrasp/.

[3] K. Minamizawa, S. Kamuro, S. Fukamachi, N. Kawakami, and S. Tachi, "GhostGlove: Haptic existence of the virtual world," in *Proceedings of ACM SIGGRAPH 2008 new tech demos*, pp.18.

[4] J. Iqbal, N. G. Tsagarakis, and D. G. Caldwell, "Four-fingered lightweight exoskeleton robotic device accommodating different hand sizes," *Electronics Letters*, vol. 51, no. 12, pp. 888–890, 11th June 2015.

[5] M. Gabardi, M. Solazzi, D. Leonardis, and A. Frisoli. "A New Wearable fingertip haptic interface for the rendering of virtual shapes and surface features," in *Proceedings of Haptic Symposium 2016*.

[6] K. Minamizawa, S. Kamuro, N. Kawakami, and S. Tachi, "Haptic interaction with virtual objects in midair using a finger-worn haptic display," *Transactions of the Virtual Reality Society of Japan*, vol. 13, no. 4, pp. 415–420, 2008.

[7] D. Prattichizzo, F. Chinello, C. Pacchierotti, and M. Malvezzi, "Towards wearability in fingertip haptics: A 3-DoF wearable device for cutaneous force feedback," *IEEE Trans. Haptics,* vol. 6, no. 4, pp. 506–516, Oct.–Dec. 2013.

[8] S. B. Schorr and A. M. Okamura, "Fingertip tactile devices for virtual object manipulation and exploration," in *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, pp. 3115–3119.

[9] C. Pacchierotti, G. Salvietti, I. Hussain, L. Meli, and D. Prattichizzo, "The hRing: a Wearable Haptic Device to Avoid Occlusions in Hand Tracking," In *Proceedings of IEEE Haptics Symposium,* 2016.

[10] D. Mochizuki, T, Nakamura, R. Kato, S. Morishita, and H. Yokoi, "Tactile sensory prosthetic hand," in *Proceedings of the Mechanical Engineering* Congress, Japan, 2012.

[11] C. Antfolk, M. D'Alonzo, M. Controzzi, G. Lundborg, B. Rosen, F. Sebelius, and C. Cipriani, "Artificial redirection of sensation from prosthetic fingers to the phantom hand map on transradial amputees: Vibrotactile versus mechanotactile sensory feedback," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 21, pp. 112–120, 2012.

[12] T. Okano, K. Hirota, T. Nojima, M. Kitazaki, and Y. Ikei, "Haptic feedback for foot sole using pneumatic pressure device," in *Proceedings of ASIAGRAPH*, 2016.

[13] Y. L. Freng, C. L. Fernando, J. Rod, and K. Minamizawa, "Submerged haptics: A 3-DOF fingertip haptic display using miniature 3D printed airbags," in *Proceedings of the ACM SIGGRAPH Emerging Technologies*, 2017.

[14] T. Nakamura, N. Nishimura, M. Sato, and H. Kajimoto, "Development of a wrist—twisting haptic display using the hanger reflex," in *Proceedings of the 11th Conference on Advances in Computer Entertainment Technology*, no. 33, 2014.

[15] A. A. Stanley and K. J. Kuchenbecker, "Evaluation of tactile feedback methods for wrist rotation guidance," *IEEE Trans Haptics*, vol. 5, no. 3, pp. 240–251, 2012.

[16] Y. Kuniyasu, M. Sato, S. Fukushima, and H. Kajimoto, "Transmission of forearm motion by tangential deformation of the skin," in *Proceedings of the 3rd Augmented Human International Conference*, no. 16, 2012.

[17] F. Chinello, C. Pacchierotti, and N. G. Tsagarakis, "Design of a wearable skin stretch cutaneous device for the upper limb," in *Proceedings of Haptics Symposium (HAPTICS)*, pp. 14–20, 2016

[18] V. Yem, H. Kuzuoka, N. Yamashita, R. Shibusawa, H. Yano, and J. Yamashita, "Assisting hand skill transfer of tracheal intubation using outer-covering haptic display", in *Proceedings of the 30th Annual ACM Conference on Human Factors in Computing Systems*, pp. 3177–3180, 2012.

[19] S. Casini, M. Morvidoni, M. Bianchi, M. Catalano, G. Grioli, and A. Bicchi, "Design and realization of the CUFF—Clenching Upper-limb Force Feedback wearable device for distributed mechano-tactile stimulation of normal and tangential skin forces," in *Proceedings of the IEEE International Conference of Intelligent Robots and Systems*, pp. 1186–1193, 2015.

[20] D. Tsetserukou, S. Hosokawa, and K. Terashima, "LinkTouch: A wearable haptic device with five-bar linkage mechanism for presentation of two-DOF force feedback at the fingerpad," in *Proceedings of IEEE Haptics Symposium*, pp.307-312, 2014

[21] M. Shibahara, Y. Vibol, K. Sato, and H. Kajimoto, "Expression of 2DOF fingertip traction with 1DOF lateral skin stretch," in *Proceedings of AsiaHaptics*, pp.21-25, 2016.