# Short Paper

## Wearable Haptic Device Presenting Sensations of Fingertips to the Forearm

Taha Moriyama and Hiroyuki Kajimoto

*Abstract*—**Several existing haptic displays used in virtual reality (VR) environments present haptic sensations generated by the fingertips in the VR to actual fingertips. However, these devices face certain challenges, such as physical interference between the devices, particularly when multi-degree-of-freedom (DOF) force needs to be presented to multiple fingers. To address this issue, we propose a haptic presentation method that transmits haptic sensations generated by the fingertips in the VR, including the direction of the force, to the forearm. We previously proposed a method to present both magnitude and direction of the force applied to the index finger using a five-bar linkage mechanism, which transmits the force sensation with two DOF to the forearm. In this study, the forces in the downward and left-right directions were obtained from the kinematics of a five-bar linkage mechanism for accurate force presentation. Additionally, we conducted a user study evaluating user grasping an object in the VR and performing task. The results verified the haptic sensation of the force transmitted by the proposed prototype to the user's forearm provides a sufficient comfort level. Furthermore, the task execution time and comfort level were comparable to those of a vibrotactile presentation presented directly to the fingertips.**

**Index Terms—Five-bar linkage mechanism, haptic transfer, multi-DOF force, virtual reality, wearable device.**

### I. Introduction

Various devices, such as haptic presentation displays that present vibration [1], temperature [2], and force [3], have been designed as haptic presentation elements for the fingers in virtual reality (VR) environments. Owing to the high density of receptors, our fingers are extremely sensitive to different types of information, such as texture, shape, weight, and temperature, when we touch an object [4]. Therefore, fingertips are the primary target for haptic devices because most tasks are performed using fingers.

The "strength and direction of the force" are particularly important haptic presentation elements when using fingers. This is because they serve as necessary information when grasping or deforming an object. Several devices that present information on the "strength and direction of the force" to the finger have been proposed, such as glove-shaped devices and devices that can be attached to the fingertip directly [3], [5]. However, the time and effort required to attach and detach most of these devices are significantly high, and the size of the device may interfere with the movement of each finger. To address these problems, we previously proposed a five-bar linkage mechanism that presents the information on the direction of the force applied to the fingertips and transmits it to the forearm [6]. This mechanism was driven by servo motors, and the direction of the force was successfully transmitted to the forearm. We determined that the dorsal and ventral sides of the forearm appropriately corresponded to the index finger and thumb, respectively. However, the force was not presented accurately as the device was driven by RC servo motor, and the effect of mapping the results of haptic on the task execution time and the comfort level of the experience in the VR environment has not been investigated.

The contribution of this study is two-fold. First, we developed a system for accurate force presentation by extending our previous research. In our previous research, 1–0 control using RC servo motors was used, and there was no calculation and evaluation of the force being presented [6]. In this research, we constructed a device capable of transmitting the direction and magnitude of the force continuously by driving a five-bar linkage mechanism using a dc motor. Based on the kinematics of the five-bar linkage mechanism, we determined the magnitude of the force that can be presented in the downward and left–right directions, and evaluated the force output by the device.

Second, we investigated the task execution time and user comfort level in terms of the experience when manipulating objects in the VR environment using the newly proposed system. In contrast to the previous report, we additionally evaluated the time spent on the task, and added the condition of vibration presentation to the forearm for comparison. The obtained results verified that the comfort level is better with the proposed system compared with vibration presentation to the forearm, and the task execution time and comfort level are comparable to the condition of a vibrotactile sensation presented directly to the finger when interacting with a VR object.

### II. Related Work

Haptic presentation devices are typically designed to transmit haptic sensations generated at the fingertips in the VR environment to actual fingertips. This section reviews the force-feedback devices that can be attached to the palm to present force sensation.

The first type of wearable haptic presentation device has a base (or ground) at a location different from the fingertip [3]. These devices can present the actual force required to bend the finger to the fingertip. However, when haptic presentation needs to be realized on multiple fingers, the size of the device increases and more time is required for attachment and detachment.

The second type of wearable haptic presentation device is worn on the fingertip. Skin deformation induced by attaching this device directly to the fingertip enables simulated force presentation. This device serves as a pseudo-force presentation device as it uses the deformation of the skin to present force and does not generate an actual force to bend the finger. Researchers have proposed several devices of this type, such as a device that can be worn on the fingertips to present the pressure sensation [7], a device capable of recognizing the shape and position of an object using skin deformation [8], a device to

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The authors are with the University of Electro-Communications, Chofu 182-8585, Japan (e-mail: taha.moriyama@gmail.com; kajimoto@kaji-lab.jp).

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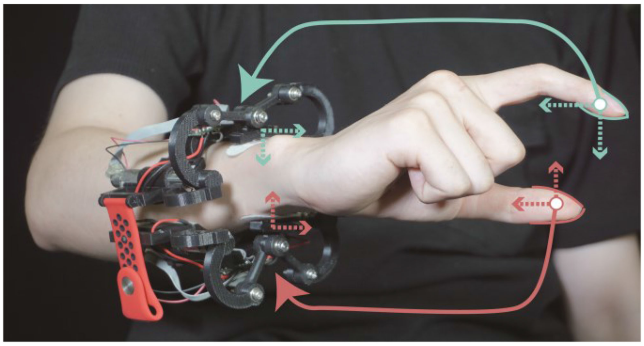

Fig. 1. Developed device design.

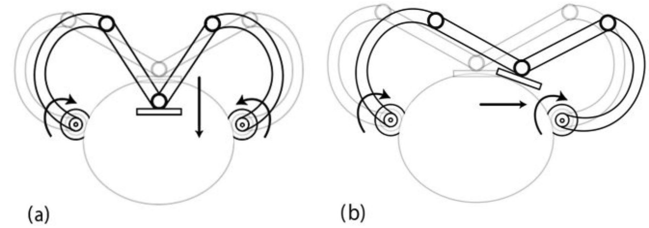


Fig. 2. Operation of the device: (a) Pressure force, (b) Tangential force.

determine the weight—which is an important cue for grasping—using only the skin sensation on the fingertips [9], and a small device that can move in three DOFs on the fingertip [10]. However, the combined weight of these devices burdens the user, particularly when presenting the force in multi-DOFs, including the direction of the force on the fingertip. Moreover, interference between devices is unavoidable.

In summary, haptic devices that can present a sense of force have certain challenges owing to the size of the actuator and the limited space available for designing and installing the mechanism. Several researchers have developed devices that present vibrotactile sensations, in addition to force sensations, to the fingers [11]. Although these devices can be miniaturized conveniently, the user's finger cannot be physically constrained, which impairs the level of comfort.

In this study, we separate the part that actually interacts with the VR object (finger) from the part that presents the haptic sensation. By presenting the haptic sensations of the finger to other parts of the body and not to the finger, the above issue is resolved. This type of haptic transfer method is common in research on sensory prostheses. In a prosthetic hand, the force received by the sensors is directly converted and transmitted to the stump [12]; approaches with multiple modalities, such as vibration, are used to present this force [13], [14]. Several studies have also attempted to place vibrators on the wrist, forearm, and shoulder as a substitute for the sense of fingers or palms [15], [16]. This study applied the haptic transfer method used in prosthetic hand-related research to VR.

Okano *et al.* investigated a method that presents haptic sensations received by the hand to the sole of the foot using a pneumatically driven device [17], suggesting the possibility of presenting haptic sensations without attaching a device to the hand. Kameoka *et al.* presented the haptic sensation of fingers in VR to the face using a suction device [18]. Furthermore, several researchers have used devices to present haptic sensation to the forearm by attaching a ring-shaped device to the forearm in VR [19]. However, transmitting the information on the direction and magnitude of the force simultaneously has not been explored.

Some studies have attempted to present pseudo-force sensations [28] by deforming the skin in the rotational [20], [21] and translational [22], [23] directions. Casini *et al.* reported a device that can present force sensation with two DOFs on the forearm [24]. However, the above devices are incapable of presenting haptic sensation to multiple locations.

## III. Device Design

Fig. 1 depicts the prototype designed in this study. The device, which was fabricated using a three-dimensional printer, weighed approximately 250g. It can be attached and detached by passing the forearm through it. Additionally, the device can be modified to various sizes by adjusting the belt on the side. An adhesive gel sheet (Vitrode F, Nihon Kohden) is attached to the area where haptic sensation is presented. The haptic sensations of force can be presented in the vertical and horizontal directions by connecting the device to the adhesive gel sheet. Haptic sensations can be presented at two locations. We determined that the dorsal side of the forearm is appropriate for the index finger, whereas the ventral side of the forearm is suitable for the thumb when touching a VR object [6]. Therefore, the upper and lower haptic presentation sites can be driven independently in conjunction with the movement of each finger.

TABLE I
Device Specifications

| | |
|---|---|
| Motor | Maxon DCX 12L |
| Gear head | GPX 12HP 35:1 |
| Link length ($L_1$, $L_2$, $L_3$, $L_4$) [mm] | 60, 35, 35, 35 |
| Device weight [g] | 250 |
| Torque (with gear) [Nm] | 0.12 |

### A. Five-Bar Linkage Mechanism

The proposed device uses a five-bar linkage mechanism, which was first introduced by Tsetserukou *et al.* as a linkage mechanism for presenting force sensation to the fingertips [25]. Since then, it has been used to present force sensations to the palm [26]. Based on this work, we designed the curved-M-shaped five-bar linkage mechanism device such that it can be worn on the forearm.

The five-bar linkage mechanism comprises five links forming a closed loop in the plane, wherein two links are driven to realize two DOF in the plane. The device uses a rotational five-bar linkage mechanism, and two dc motors (Maxon Motor DCX12L, Gear GPX12HP 35:1). The two motors can be driven in the same direction to present a friction sensation to the skin, or in opposite directions to present a pressure sensation (Fig. 2). Table I lists the length of the link and specifications of the motor used in the device.

In our previous research, the RC servo motor was used to control the 1–0 position, and the presented force was not calculated and evaluated [6]. In this study, we developed a system that can present the direction and magnitude of the force continuously using a dc motor. The magnitude of the force that can be presented was measured based on the kinematics of the aforementioned five-bar linkage mechanism and evaluated through a force measurement experiment.

### B. Force Measurement

Fig. 3 illustrates the five-bar linkage mechanism, wherein $L_3$ is subjected to two target forces, namely $F_{23}$ and $F_{43}$, from contact points B and C, respectively. Additionally, $L_4$ is subjected to two target forces, $F_{34}$ and $F_{54}$, from contact points C and D, respectively.

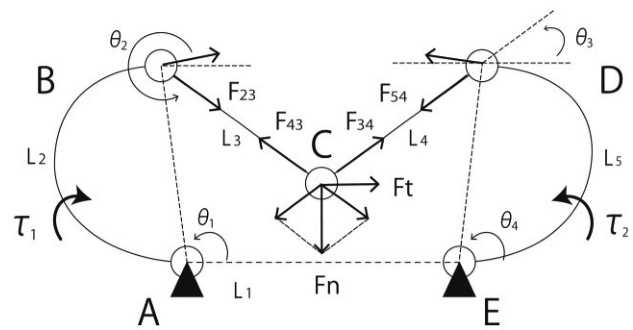


Fig. 3. Five-bar linkage mechanism.

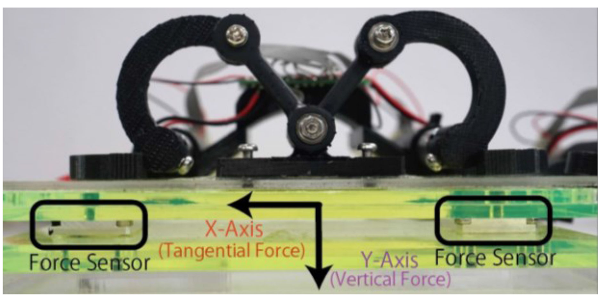


Fig. 4. Force measurement system.

On this basis, we derived the horizontal and vertical forces at the ends, namely $F_t$ and $F_n$, respectively, using (1), where $\boldsymbol{\tau}$ denotes the torque, and $l$ denotes the length of each link. The force output changes depending on the initial position of the haptic presentation point C. The initial position of point C measured and simulated in this experiment was on the straight line of the two motors A and E ($\theta_1 = 50^\circ, \theta_2 = 300^\circ, \theta_3 = 60^\circ, \theta_4 = 130^\circ$), and the same condition was applied in the user study by taping the arm and adjusting the height of point C for each participant. The maximum vertical force output of the device was approximately 6.0 N.

$$\begin{bmatrix} F_t \\ F_n \end{bmatrix} = \begin{bmatrix} \sin(\theta_1 - \theta_2)\cos(\theta_2) & -\sin(\theta_4 - \theta_3)\cos(\theta_3) \\ -\sin(\theta_1 - \theta_2)\sin(\vartheta_2) & \sin(\theta_4 - \theta_3)\sin(\theta_3) \end{bmatrix} \begin{bmatrix} \frac{\tau_1}{l_2} \\ \frac{\tau_2}{l_5} \end{bmatrix} \quad (1)$$

Subsequently, we measured the horizontal and vertical force output from the device using two three-axis force sensors (DSA-03A, Tec Gihan Co., Ltd.). An acrylic plate was attached to the top of the force sensors, and the cylindrical sensing part of the sensor was inserted into the hole to measure the force in the X-axis or horizontal direction. The skin-contact part of the device was placed on the acrylic plate, along with a sufficient weight to prevent the device from moving owing to internal force (Fig. 4).

Initially, we recorded the vertical force by driving the two-section motor in opposite directions, and the pulse-width modulation (PWM) ratio was varied from 0% to 100% (9V) in steps of 10%. After calibrating the force sensors for each recording, the data were observed and recorded for five times each. Fig. 5 illustrates the output generated in the vertical direction, which changes almost linearly as the voltage value increases. The maximum output was approximately 6.1 N, which is almost equal to the value calculated using (1).

Furthermore, we measured the force output when the left and right motors were rotated in the same and opposite directions. The results

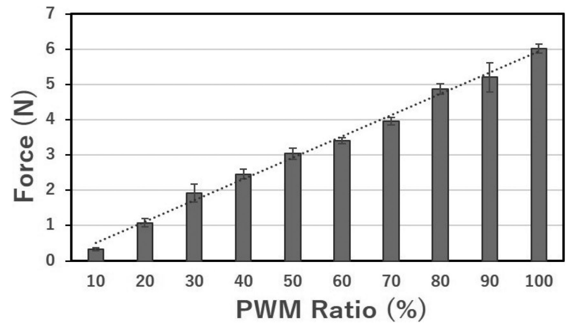


Fig. 5. Output generated when the motors are rotated in opposite directions (pressure force).

obtained that the maximum horizontal force output is approximately 3.2 N. When the vertical and horizontal forces are presented at the maximum output, their values are approximately 3.9 N and 2.0 N, respectively.

## IV. User Study

We considered the task of grasping an 8-cm wide VR object in the VR environment and placing it at the target position while wearing the prototype device. It has previously been reported that presenting vibrotactile sensations only and also vibrotactile and force sensations directly to the finger's interaction with the VR object as a haptic presentation method in the VR environment aids in performing the task [1], [27], [29]. In this experiment, in addition to the condition of force haptic presentation using the proposed device, we considered other conditions, namely task performance without haptic presentation, direct vibrotactile presentation to the finger interaction with the VR object, and vibrotactile presentation to the forearm.

### A. Experimental Conditions

We used WindowsMR (Lenovo) as the head-mounted display (HMD) for visual presentation. An optical motion capture device (OptiTrack Trio, Acuity Inc.) was used to track the user's thumb and index finger, and Unity (2019.4.16f1) was used to draw the presentation image. The prototype device was connected to a personal computer through a microcontroller (ESP32, Espressif Systems). The experiment was performed considering the following conditions:

1. Visual information only
2. Vibrotactile presentation to the fingertips
3. Vibrotactile presentation to the forearm
4. Haptic presentation to the forearm using the prototype

In condition 1, only the image drawn by the HMD was presented and no sensation was presented to the body. In condition 2, a voice-coil vibrator (Haptic Reactor, Alps, Alpine) was placed on the fingertip. To present the vibrotactile sensation to the forearm in condition 3, the voice-coil vibrator was placed in the same area as the forearm using the proposed device under condition 4. The voice-coil vibrator was driven at 160 Hz in both conditions 2 and 3. As Pacinian corpuscles, which are known to exist in both hairy and hairless areas, respond to high frequency vibration, and 160 Hz is the resonant frequency of this voice-coil vibrator, sufficient vibration can be perceived in each part of the finger and forearm [4]. The amplitude of the vibration varied linearly with the amount of push-in (pressure) when the subject touched the 8-cm wide VR object. The amplitude of the voice-coil vibrator was varied linearly with a maximum of 4 cm push-in to the VR object. The vibration intensity of the voice-coil

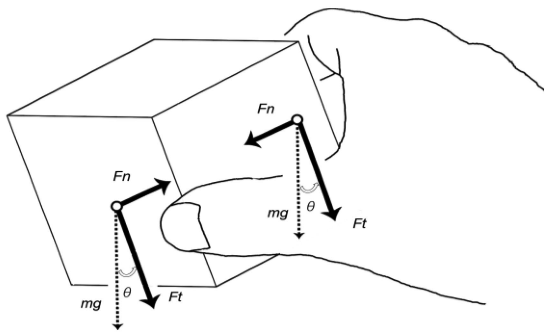


Fig. 6. Calculation of the force output by the proposed device.

vibrator was 0.3 G at 1 cm and 6.9 G at 4 cm, which confirmed that the intensity of vibration varied almost linearly.

In condition 4, the haptic sensation was presented to the forearm using the proposed device. Based on the results of the previous study, the haptic sensation was presented to the ventral and dorsal parts of the forearm as the areas corresponding to the thumb and index finger, respectively [6]. The haptic sensation was presented 5 cm from the place where the wrist was bent toward the forearm. The VR object was touched with a maximum of 4 cm push-in, and the force applied to the forearm was varied linearly.

When the object was grasped and lifted, the force was applied in the direction of gravity (vertical direction) in addition to the pressure sensation. Equations (2) and (3) were used to calculate the force presented by the proposed device, where $F_t$ denotes the horizontal force, $F_n$ the vertical force, $m$ the mass of the object, $g$ the acceleration due to gravity. and $k$ Hooke's coefficient (Fig. 6).

$$Fn = kx \tag{2}$$

$$Ft = mg\cos\theta \tag{3}$$

The strength of the stimulus was adjusted by the experimenter to be roughly equivalent to the strength of the vibration when touched by a finger. As a result, the vertical direction was set to a maximum of 3.5 N and the horizontal direction was set to maximum of 2.0 N.

Eleven members of our laboratory, ages between 21 and 27 years, participated in the experiment. During the experiment, the participants were asked to move an 8-cm wide VR object by 30 cm and place it in a specified position. We performed a total of 20 trials, five trials under each of four experimental conditions, and recorded the time from touching the VR object to placing it. The virtual finger was kept on the surface of the virtual object and did not penetrate during grasping.

The participants responded to the haptic information presented to them on a 7-point Likert scale, ranging from 1 (not comfortable) to 7 (comfortable) after each trial. The participants were asked to make a comprehensive decision (without evaluating specific items such as the weight of the device and realism) to determine whether the device functioned at a minimum as a haptic device. The order of the haptic presentation conditions was randomized for each participant. The time taken to complete each trial was recorded under each haptic condition. The task execution time was recorded from the moment when both fingers touched the VR object (detecting that the object is grasped) to the moment when the object was accurately placed in the specified position. The participants were asked to manipulate the object without haptic presentation for a single round trip as practice, and then were asked to place an object at a target location accurately during the experiment.

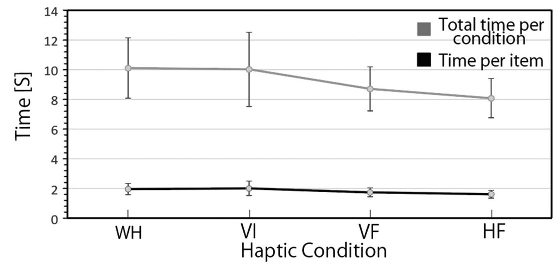


Fig. 7. Task execution time.

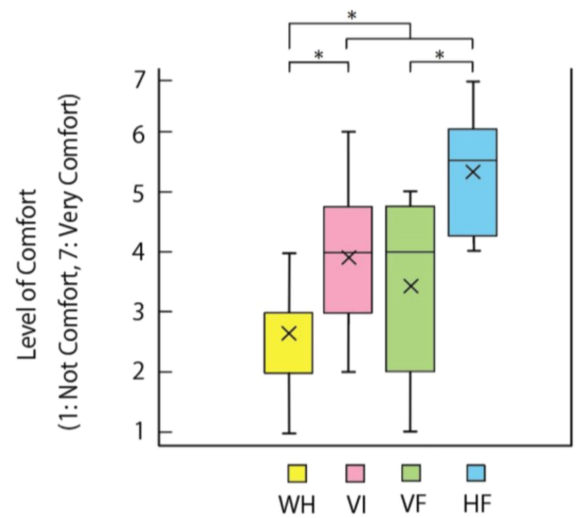


Fig. 8. Comfort levels under each haptic condition.

## B. Experimental Environment

The finger position acquired by the OptiTrack Trio was linked to the VR finger position in the video, the voice-coil vibrator, and the proposed prototype. The VR object, a desk, and the target position where the VR object must be placed were drawn in the VR environment. During the experiment, the subjects wore the HMD and headphones, and white noise was played to screen the driving sound of the actuators.

## C. Experimental Results

Fig. 7 illustrates the average time required to move the VR object to the specified position for each haptic presentation condition, where WH denotes without haptic condition, VI the vibrotactile feedback to the fingertips condition, VF the vibrotactile feedback to the forearm, and HF the haptic presentation to the forearm using the proposed device. Fig. 8 depicts the responses of the subjects to the comfort level of the experience for each haptic presentation condition.

First, we examined whether there was a difference in the task execution time for the different conditions. We conducted a one-factor analysis of variance, wherein the independent and dependent variables were the haptic condition and the execution time, respectively. Based on this analysis, we determined the difference in the execution time of the task in each presentation condition (Fig. 7). No statistically dominant effect was observed ($F(3,30) = 3.653$, $p = .068$), however, the VR object was moved to the specified position with the lowest execution time in the condition using the proposed device.

Next, we examined whether there was a difference in the evaluation of comfort level for each condition. We performed a nonparametric analysis of variance using the Friedman method and the Wilcoxon signed rank test for post hoc evaluation. We found a significant difference at the 5% level between HF, WH, and VF ($p < 0.05$). Moreover, when we compared condition VI with that of WH and VF, the vibrotactile presentation to the finger was determined to be significantly higher ($p < 0.05$). Finally, during the questionnaire survey, all 11 participants responded that the condition using the proposed device was the most comfortable.

## V. Discussion

We analyzed the experimental results of the aforementioned four conditions and found no difference in the time required to manipulate the VR object. On the other hand, in the condition involving only visual information, the time to manipulate the VR object was approximately 1.96 s, whereas in the case of the proposed system, the object was manipulated in 1.62 s. Therefore, the proposed device seems to reduce the execution time for simple tasks that require repetition.

Conversely, we observed a significant difference in the results of the level of comfort while performing the task, although the task execution time was similar. The user experience in terms of haptic presentation using the proposed device was significantly better than that without the haptic sensation condition and vibrotactile presentation to the forearm. Several subjects commented that although both conditions were symbolic haptic sensations, the presentation of changes in the magnitude and direction of the force from the device in response to the posture of the object was more comfortable than in the vibrotactile presentation condition. Further, the participants commented that “I clearly felt a sense of grasping an object with the newly proposed device, not just cognition of touching or grasping an object, even if the touch was not on the fingertips.”

In the vibration stimulus, the amplitude of the voice-coil vibrators varied owing to the vertical force applied to the VR object, and the presented stimulus remained constant even when the posture of the grasped object changed. In the case of haptic presentation using the proposed device, the magnitude and direction of the force applied to the forearm changed based on the variation in the posture of the VR object. Furthermore, the force information associated with the manipulation of the VR object was integrated with the sensation of the finger movement, which ensured comfortable interpretation of information in comparison with that in the vibrotactile presentation. This may have led to a stronger level of comfort.

In the condition of vibrotactile presentation to the finger, a significant difference was observed between the condition of visual information only and that of vibrotactile presentation to the forearm. This implies that in the case of vibrotactile presentation, transferring the haptic sensation to the part of the body that interacts with the VR object directly generates a higher level of comfort compared to the haptic transfer method.

Conversely, no significant difference was observed between the presentation of vibration haptic sensation to the fingertips and the presentation of force haptic sensation using the proposed device. This is possibly owing to the small population and the experimental design; the task of simply picking up an object and moving it does not fully exploit the directionality and magnitude that the prototype device can render. It is also possible that the accuracy of the stimuli affected the results. In this study, the strength of the stimuli was adjusted subjectively by the experimenter, but in practice, the strength of the force or vibration felt at the fingertips should be matched with the strength of the force presented to the arm with higher precision. For example, Biggs and Srinivasan measured the difference in the strength of force felt at the fingertips and the arm [30]. Also, the strength of the vibration between the fingertip and arm should be subjectively matched. However, the results of the questionnaire survey indicated that all participants experienced the most comfort when using the proposed device. This implies that the haptic force transferred by the proposed device can provide the same level of comfort as that of the vibration haptic presentation, which is frequently used as a haptic presentation method in VR environments. It is also possible to use a combination of vibrotactile presentation to the finger, which is highly evaluated for comfort, and force presentation to the arm. By presenting vibrations to the fingers during a collision, a quick response can be achieved and, by presenting the applied force on the arm, there is no need to install large devices on multiple fingers, thus eliminating interference between devices.

## VI. Conclusion and Future Work

We developed a prototype device that uses a five-bar linkage mechanism to transfer the haptic sensation of fingertips from a VR environment to the forearm. The device is capable of presenting both the magnitude and direction of force accurately. We investigated the quality of the experience in terms of manipulating a VR object using the device. The obtained results verified that the user experience is more comfortable than that of vibrotactile presentation to the forearm, and the comfort level was comparable to those of a vibrotactile presentation presented directly to the fingertips. However, comfort does not define the overall VR experience and it is therefore necessary to evaluate the device from various aspects such as weight, realism, and ease of use. Furthermore, to obtain a better evaluation than the haptic presentation device to the fingertip, there is room to consider whether the force applied to the finger should be presented to the arm with more DOFs.

The proposed device is a platform that can be used to study further psychophysical effects. In future work, we intend to compare the proposed system with a force presentation device to the fingers and determine whether the task execution time and realistic experience are improved. Additionally, we intend to design a device, based on our proposed device, which can present vibration and temperature. With the newly designed device, we intend to investigate the change in task execution time considering the training time, and determine whether the haptic transfer device can be made more comfortable.

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