# PaCaPa: A Handheld VR Device for Rendering Size, Shape, and Stiffness of Virtual Objects in Tool-based Interactions

**Yuqian Sun**[1], **Shigeo Yoshida**[12], **Takuji Narumi**[12], **Michitaka Hirose**[1]
[1]The University of Tokyo, [2]JST PRESTO
Tokyo, Japan
{y_nakayama,shigeodayo,narumi,hirose}@cyber.t.u-tokyo.ac.jp

**Figure 1: (left) PaCaPa is a handheld device with two wings that open (a) and close (b) to render a sense of pressure on the palm and fingers when the virtual tool in a user's hand makes contact with virtual objects. (right) Our device can render a target object's size with different open angles when the hand is wielded in the same way.**

## ABSTRACT

We present PaCaPa, a handheld device that renders haptic feedback to a user's palm when the user interacts with virtual objects using virtual tools such as a stick. PaCaPa is a cuboid-shaped handheld device with two wings that open and close. As the user's virtual stick makes contact with a virtual object, the wings open by a specific angle to dynamically change the pressure on the palm and fingers. The open angle of the wings is calculated from the angle between the virtual stick and hand direction. As the stick bites into the target object, a corresponding feedback force is generated. Our device enables three kinds of renderings: size, shape, and stiffness. We conducted user studies to evaluate the performance of our device. We also evaluated our device in two application scenarios. User feedback and qualitative ratings indicated that our device can make indirect interaction with handheld tools more realistic.

## CCS CONCEPTS

• **Human-centered computing → Haptic devices**;

## KEYWORDS

Virtual Reality, Haptics, Tool-based interaction

**ACM Reference Format:**
Yuqian Sun, Shigeo Yoshida, Takuji Narumi, Michitaka Hirose. 2019. PaCaPa: A Handheld VR Device for Rendering Size, Shape, and Stiffness of Virtual Objects in Tool-based Interactions. In *Proceedings of CHI Conference on Human Factors in Computing Systems Proceedings(CHI 2019), May 4-9, 2019, Glasgow, Scotland UK.* ACM, New York, NY, USA. Paper 452, 12 pages. https://doi.org/10.1145/3290605.3300682

## 1 INTRODUCTION

The present computer graphic and display technologies make the VR experience more realistic visually. In these VR spaces, users can not only watch, but also interact with objects in the scene. However, the lack of haptic feedback reduces a sense of presence. Generally, vibrotactile feedback is used as a method of haptic rendering. Although it can notify the collision and supports delicate manipulation [7], vibrotactile

---

*CHI 2019, May 4–9, 2019, Glasgow, Scotland Uk*

ACM ISBN 978-1-4503-5970-2/19/05…$15.00
https://doi.org/10.1145/3290605.3300682

feedback is more often used as a notification of collision and is not suitable for continuous touching. In addition, rendering by vibrotactile feedback is very limited and can be insufficient for rendering information such as shape and stiffness.

Researchers have developed various other haptic devices that go beyond simply using vibrotactile feedback to solve this problem. Researchers have proposed wearable devices and encountered-type haptic display [6] solutions. However, wearable devices, such as exoskeleton gloves, can be a disadvantage for users to wear, and the area in which the equipped device can move is limited. To solve these problems and to easily render haptic information, handheld-devices have recently been developed. However, most of these devices are proposed for bare-handed interaction in VR.

In this paper, we focus on indirect interaction. In a virtual environment, users often hold a tool in their hand such as wielding a sword or a bat in a sports training. We refer to this type of interaction that a user experiences by making contact with an object via a handheld tool as *tool-based interaction* or *indirect interaction*. By focusing on this interaction, it becomes natural for users to hold a device.

We present PaCaPa as a new handheld device for VR in tool-based interaction. PaCaPa is a device with two wings which open and close to give dynamically changed pressure to the palm and fingers. The device is designed to enhance the experience of making contact with objects in tool-based interaction by giving the same pressure as would be sensed in a collision. The name of the device, *PaCaPa*, is an acronym of *Prop that Alters Contact Angle on PAlm*. In addition, it relates to the Japanese expression of sound that occurs when the device's wings open and close: "pacapaca".

In the following section, we describe the previous work on VR haptic devices. We then present the design and implementation of our device and describe studies that we conducted to evaluate our proposed device. The results of our study indicate that our device can render realistic size, shape, and stiffness of a target object by giving a pressure sensation to a user's palm and fingers. In addition, we list some examples of applications that feature our device and discuss the users' comments and feedback.

This paper provides the following core contributions:

(1) A concept to present a sensory perception of pressure generated when the handheld tool bites into a target object to render the collision in virtual space.
(2) Design and implementation of PaCaPa, a handheld haptic device for tool-based interaction.
(3) Results of user study with tool-based interaction using our device. The results suggest that the participants can recognize relative size differences, distinguish basic shapes, and discern hard and soft objects with our device.

## 2 RELATED WORKS

### Wearable Haptic Device

In VR applications, a user often interacts with virtual objects using his/her hand. Giving haptic feedback to the user's hand when the user touches something is a basic idea.Using a wearable haptic device is one simple solution to rendering haptic information. Wearable haptic devices can be divided into two main categories, namely exoskeletons [5, 13, 22, 27, 28] and finger-mounted haptic devices [8, 9, 24, 32]. Exoskeletons are devices that cover the user's hand and provide force feedback to the fingers. Although these devices can present haptic feedback directly, they require the user to spend a certain amount of time putting on and adjusting the devices. In addition, the device is costly because many actuators are required for one device. Finger-mounted haptic devices have been developed with the idea of attaching devices on the fingers to simplify the device design. This reduces the cumbersome process of wearing a device on the hand but still requires an additional attachment to the hand.

### Encountered-type Haptic device

Grounded devices [2, 15, 18, 21] are another solution that can realistically render virtual objects without troubling users with the process of putting on and wearing the device. In these devices, the base of the device is attached to something in the environment and the user grasps a part of the device that is connected to the base with a joint or a string. When users hit a virtual object, the device gives a kinesthetic force. In this way, the device can render a bigger force and an area that the user cannot invade in virtual space. However, since the device is environmentally grounded, the area that the device can render is limited. Non-grounded encountered-type haptic displays [26, 31] are proposed to solve this area limitation problem. These encountered-type haptic devices can render shape, but the fact that they require a large and heavy apparatus is still a shortcoming.

### Handheld Haptic Device and Tool-based Interaction

Handheld haptic devices are currently being explored as a solution to the troublesome setup and the immobility problem. Vibrotactile feedback is one of the most used types of haptic feedback given when the users interact with a virtual object using the device. However, this kind of feedback is only used for touching or notification of contact and cannot produce the real contact and resistance forces generated from the contact. Some devices [4, 10, 29] attach a mechanism that renders the surface of the virtual objects or a resistance force for the fingertip, but these limit the pose of the hand and sometimes cause conflict between the virtual and real hand pose. Some devices focus on tool-based interaction by adding a haptic feedback mechanism to the tool-shaped device [12, 14, 17, 19]. This makes the real pose and virtual pose consistent, but the application is limited to one kind. Pupop [25] and Virtual Mitten [1] enhance the grasping experience, but some interactions such as hitting are not supported.

In this paper, we focus on tool-based interactions such as hitting an object with a stick-shaped tool. There are many VR applications for tool-based interactions as well as bare-handed interactions. We present a handheld device that provides ease of wearing, supports various uses in tool-based interactions, and creates substantial resistance force produced by contact. There are some devices that can render the force, such as torque, pulling force, and shear force applied to the tool [3, 23, 30], but these are not enough to express a sense of collision. We focused on other forces and created a device which is simple and easy to integrate with other devices to create a more realistic experience with the combination of haptic feedback. Some devices can render the property of the tool itself, such as weight and shape [20, 25, 33] and we believe that changing the form of the tool with relative posture and position can create haptic feedback in tool-based interaction. HapMAP [16] uses a box-shaped device which can give a sensation of a handrail by changing the direction of the box to help users navigate. We used a similar mechanism but focused on the relative posture and pressure.

## 3 DESIGN AND IMPLEMENTATION

When we interact with an object by touching or hitting it with various tools, including sticks and swords, we receive haptic sensations. For example, assume there is a hard cube in front of a person and he/she is trying to hit the cube with a stick. When the stick touches the cube, he/she senses vibration. If he/she keeps hitting the cube with the stick, he/she will feel pressure on his/her palm since the stick cannot go the way he/she may have intended it to go. Users will feel the stick rotate in the opposite direction to user's intention to move with their holding hand as an axis. In VR applications, users often have a stick shaped tool in their hand, such as a sword or a racquet. If users have the tool in their hand and interact with an object in virtual space, the same response should occur. To implement this touching sensation, we created a box-shaped device which represents the part of the stick held by the user. The device has two wings that can open and close, providing for a sense of pressure to be created when held in the user's hand.

### Hardware Design

The final design of our device is shown in Figure 2. To build the mechanism that allows wings open and close, we used one servo motor (TowerPro 9g digital servo SG92R) for each wing. These two servo motors were mounted in the box and the wings were attached to the motors. Both the base and the wings were 3D-printed and made of PLA (polylactic acid). By manipulating the two motors, the wings can open and close in a range of 0 to 90 degree. This hardware design imitates part of the stick so that the user can hold it like a stick. As the wings open, the device gives pressure to three fingers, namely the middle, ring, and smallest finger as well as to the skin between the base of the index finger and the base of the thumb. These areas of sensitivity are based on the observations relating to the pressure that is felt when holding and using a stick and hitting something.

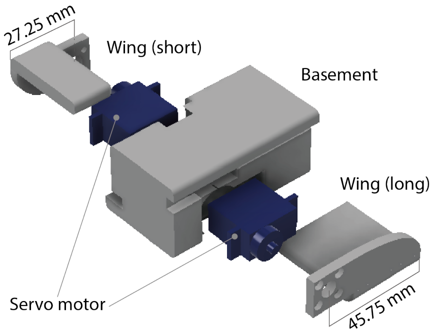


**Figure 2: Exploded view of 3D model showing components of PaCaPa.**

**Table 1: Technical specifications of our device**

| Variable | Value |
|---|---|
| Weight | 65 g |
| Max Speed | 0.1 sec / 60deg |
| Torque | 2.5 kg / cm |
| Dimensions | 32 mm × 32 mm × 70 mm |
| Power Consumption | 6 V |

We expect the device to be wireless in the future. For the sake of simplicity and rapid implementation of the prototype, we used an external power supply. The latency of PaCaPa is 50 ms. Other detailed specifications are shown in table 1.

### Software Architecture

The basic software architecture is shown in Figure 3. We used a microcontroller (Arduino UNO) to control the two servo motors in the device through pulse-width modulation (PWM). A Unity 3D game engine is used for rendering the VR applications. We used USB serial communication to connect the microcontroller and PC at a baud rate of 9600. The Unity 3D game engine handles the communication with the device and determines the wings' angle.

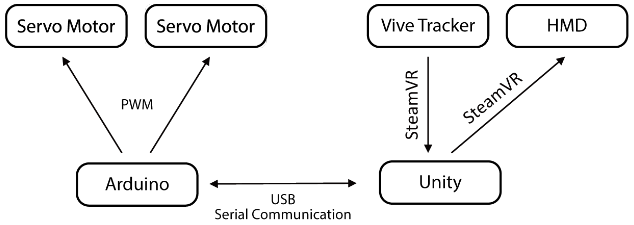


**Figure 3: Software Architecture of PaCaPa.**

### Integrating device and VR

Due to the fact that there is a gap between the area that the hand can move in reality and the area that it can move in the virtual environment, it is not sufficient to simply render a virtual stick according to the position of the hand and the rotation. Therefore, we established a method to calculate the position and direction of the virtual stick using the constraint-based god-object method [34] as a reference. In our method, we made use of a hand-based stick and a god-object. A hand-based stick is one that renders in correspondence to the hand position and direction. A god-object is a virtual stick that does not penetrate the target object and is in the same location and rotation as the hand-based stick when the hand-based stick is not in conflict with target objects. When the hand-based stick hits the object for the first time, we determine whether the stick penetrates the target object if the stick moves from the god-object location to the hand-based stick location. If it hits anything, the god-object is put at the new collision point calculated from connecting the hand-based stick and te god-object. The god-object is calculated to intersect the new collision point and hand position. If it does not hit anything, the god-object starts to follow the hand-based stick. The virtual stick is always rendered at the point of the god-object. The degree of the device's wings corresponds to the angle between the hand-based stick and the virtual stick (Figure 4). This allows for a stronger sense of pressure as the stick connects with the target object.

## 4 EVALUATIONS

We designed three studies to evaluate our proposed system. As discussed in the related works, the properties often rendered with haptic devices are size, shape, stiffness, texture, and weight. Among these properties, we focused on size, shape, and stiffness, which is entailed in the application that users touch or hit with the handheld tool.

### User Study1: Rendering Size

For this study, we intended to achieve an understanding of rendering size with PaCaPa. Therefore, we allowed participants to hold PaCaPa in their hands and explore an empty virtual environment by touching and hitting cubes of various sizes with the virtual stick. The participants were then asked to identify the size of the target cubes using only a pressure sensation as presented by PaCaPa.

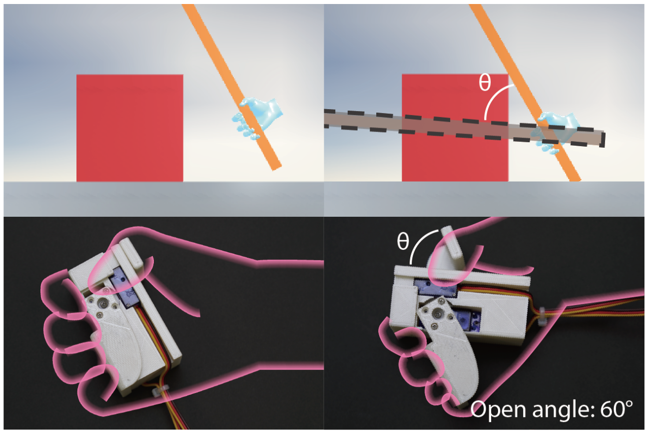


**Figure 4: (left) When the hand-based stick touches nothing, the virtual stick follows the hand-based stick. (right) When the hand-based stick penetrates target object, the virtual stick is positioned to not intersect the objects. The open angle presented by PaCaPa corresponds to the open angle of hand-based stick and the virtual stick.**

*Participants.* There were 18 participants recruited (10 male and 8 female), ages 18 to 54 (mean = 29.7). Sixteen participants were right-handed. Each participant received a $9 (¥1,000) Amazon gift card for their participation in the study.

*Experimental Setup.* As for apparatus used in the experiment, we prepared a Head-Mounted Display (HMD) and the PaCaPa as well as a controller for the input of size values. To get the position and rotation of the hand, we also prepared a tracker that could be attached to the back of the participants' right hand. The HTC Vive HMD, tracker and controller were used to present the virtual reality content. The participants wore an HMD on their heads and a band with a tracker on their right hand while holding the PaCaPa in the right hand and a controller in the left hand.

*Method.* In this study, the size of cube was changed while the distance between the closest side of the cube and the sitting position was fixed (Figure 5). The distance to the participant's feet is 1 meter. There are five cube sizes (0.5, 0.75, 1.0, 1.25, and 1 meter on each side). We showed a cube with the size of 1 meter in the training session.

We also changed the direction in which the device was held. By adding these conditions, we intended to clarify how participants perceive when there is an inconsistency between the haptic stimuli and visual presentation. We allowed the participants to hit the cube from the upper side. Therefore, 0°

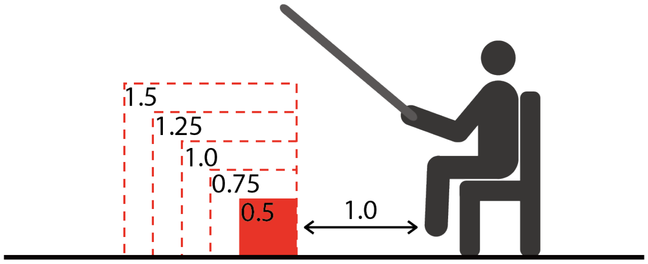


**Figure 5: Cubes of five sizes are presented in study 1.**

means the direction of the given sense of pressure matches the visual input. There were five patterns of size, three of device direction (0°, 90°, 180°) and a total of 15 samples.

*Procedure.* At the beginning of our study, a training session was held to allow participants to become acquainted with the manipulation of the controller and virtual stick. Participants held our device in their right hands at a direction of 0°. A blue and red target cube were shown in VR space. The size of blue cube corresponded to participant input. Participants were taught to input the values using the controller. The participants could also see the stick and the virtual hand in the right hand in VR space. Participants were asked to hit and press against the cube from the upper side, for presenting tactile feedback correctly. Participants were informed that the target cube and stick would not be rendered in testing sessions and that the hand corresponded to the right hand in reality. This means that the direction of the virtual hand did not match the stick direction in the virtual environment. Participants were then asked to practice thoroughly during the training session.

During the testing session, only a blue cube and virtual right hand were rendered. In this way, participants could predict the cube size using only a tactile cue. In addition, the hand could help participants to get an idea of the distance to the cube. Before the start of each trial, the device was placed on the participant's hand in a specific direction. As there was no time limitation in each trial, participants were asked to explore the virtual environment until they had enough confidence about the size of the red cube. Then, the next step was to change the size of the blue cube to match the size that the participants assumed the red cube was and then proceeded to the next trial. All trials were randomized.

*Results and Discussion.* Figure 7 shows the sizes perceived by participants with the device held in the right hand, giving a sense of pressure for a specific direction. The size represents the side length of the cube. A linear approximation was plotted as calculated from the least squares method. Each linear plot can be represented as

(1) 0° from correct device direction
$y = 0.832x - 0.0639$
(2) 90° from correct device direction
$y = 0.884x - 0.110$
(3) 180° from correct device direction
$y = 0.804x - 0.0708$

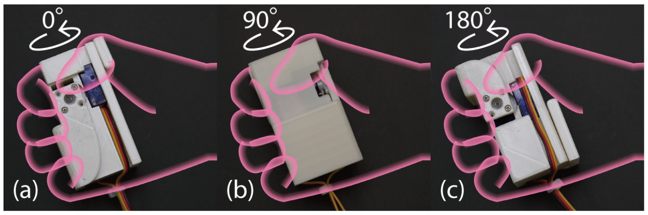


**Figure 6: Pattern of device direction used for study 1. Degrees represents the rotation degree from the direction which the device can render the haptic stimulus correctly.**

The correlation coefficient is 0.856, 0.848, 0.804 and the coefficient of determination is 0.734, 0.719, 0.733 for 0°, 90°, 180°.

The result indicates that our method can tell the relative size even though the size is not precise. This result does not change according to the direction of the pressure stimulus. However, some participants remarked that they felt a strange feeling relating to the stimulus in some trials. P12 said "*I was surprised at the reality of hitting the cube with the stick but I sometimes felt the gap between visual and tactile stimulus when device direction was changed*". This suggests our participants can recognize size even though the stimulus direction does not match the visual direction because they only care the absolute degree, but the sense of realism decreases.

There is an interesting tendency for the participants to perceive the cube as being smaller than actual size. This is because PaCaPa does not provide stimulus when participants just touch virtual object and start opening when the stick bites into the object. Another interesting comment that we received from participants was that the object they perceived were not exactly shaped as a "cube". Some said that the perceived height was longer than the width. Some also mentioned that the cube was not symmetrical. In this study, we only tested the height perception, but these comments suggest that height and width perception via indirect interaction may differ.

## User Study 2: Rendering Shape

Since the result of study 1 shows that the direction of pressure given by the device does not influence size perception, we hypothesized that participants would be able to distinguish shapes without the instruction of hand wielding direction. We conducted two user studies to see whether the participant

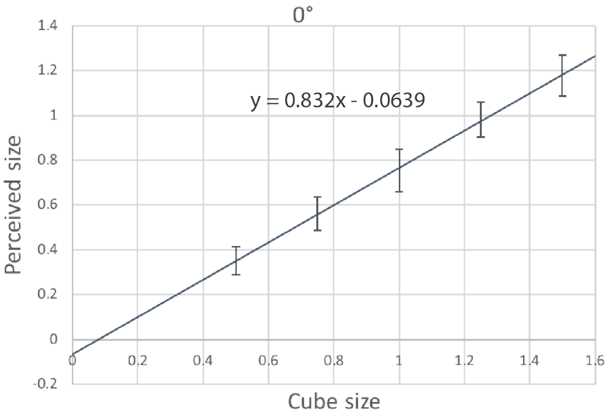


**Figure 7: Perceived size versus actual size. The direction of the device is 0°. Error bars indicate 95% bootstrap confidence interval.**

could distinguish shape only with tactile cues in user study 2.1 or with both tactile and visual cues in user study 2.2.

*Participants.* In study 2.1, 12 participants (8 male and 4 female) were recruited, ages 18 to 54 (mean = 30.3). In study 2.2, 14 participants (10 male and 4 female) were recruited, ages 18 to 43 (mean = 29). All participants in each experiment are right-handed. Each participant received a \$9 (¥1,000) Amazon gift card for their participation in the study. Note that four individauls participated in both experiments.

*Experimental Setup.* We used the same setup for the apparatus as used in study 1 including an HTC Vive HMD, controller, tracker, and our proposed device.

*Method.* We prepared three shapes for three different (height, width) pairs (Figure 8):

- square - (1, 1), (1.25, 0.75), (0.75, 1.25)
- circle - (1, 1), (1.25, 0.75), (0.75, 1.25)
- triangle - (1, 1), (1.25, 0.75), (0.75, 1.25)

*Procedure.* Similar to in study 1, both a training and testing session took place and there was no time limitation for all trials in studies 2.1 and 2.2. During the training session, the target shape was placed in front of the participants. The participants could see his/her hand holding a stick in their right hand. The participants could change the shape of the target object using the controller. The participants could try three shapes with the size of (1, 1) in the testing session. Participants were allowed to become acquainted with the use of the controller for manipulation and stimulus.

During the testing session of study 2.1, similarly to the first study, only a virtual hand representing the real hand was shown in VR space. The stick and target object became transparent. Participants were asked to explore the VR space with a transparent stick and to describe the shape they perceived from the nine shapes using the controller.

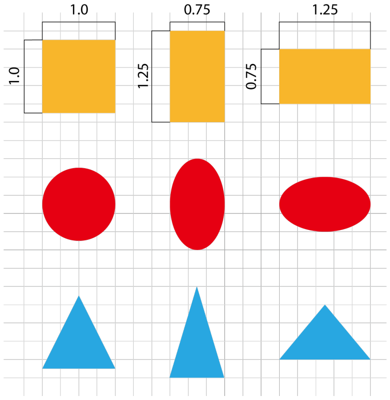


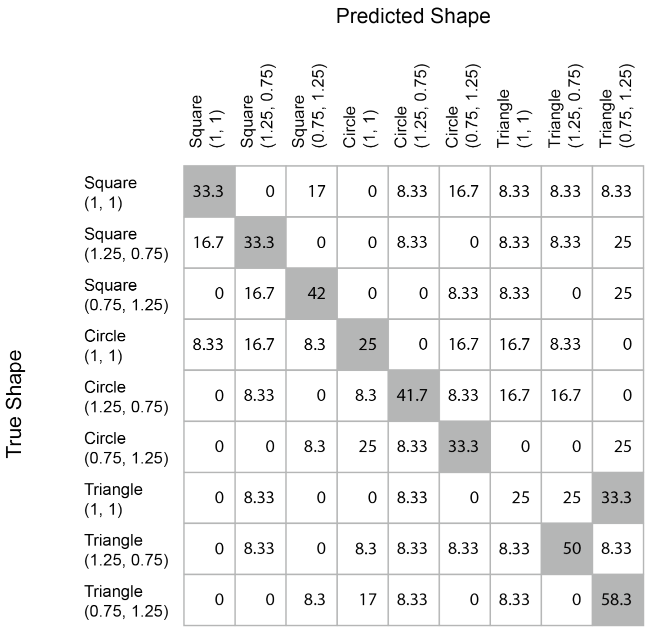
**Figure 8: Shapes presented in study 2.**

During the testing session of study 2.2, both the hand and target object were shown in VR space. However, the tactile stimulus from PaCaPa did not always match the visual stimulus. Participants could switch visually shown shapes using the controller and were asked to identify the visual shape that matched the shape represented by the tactile stimulus.

In both studies, every shape was tested in random order for a total of nine samples.

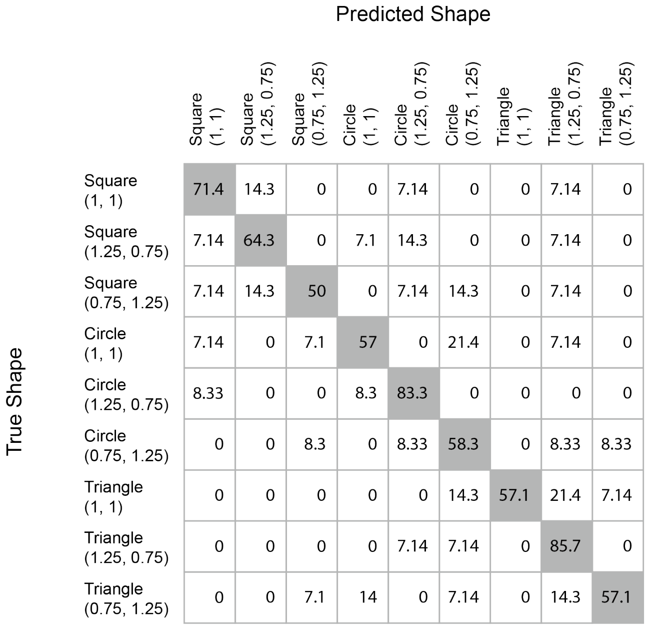
*Results and Discussion.* The results are summarized in a confusion matrix on Figure 9 and 10. As Figure 9 shows, the shapes with the highest percentage participants answered are mostly correct, but the percentage itself is not significantly high with the lowest being 25. This is due to the fact that having no visual cues made it difficult for participants to identify the point at which stick makes contact. As P10 mentioned, "*it is hard to know the dimensions of the shapes since there is nothing shown in VR space and that makes it even harder to know the point at which I am touching*".

This reasoning is also supported by the result of study 2.2. The overall percentage of success in predicting the correct shape is increased. However, some of the percentages are still low, with the lowest being 50. As the comment from study 1 shows, the perception difference of height and width affects the result. If the height and width are ignored and only the primitive shape prediction is considered, percentages are 76.2, 79, and 81 for square, circle, and triangle, respectively. P14 commented that "*I can know whether I am touching the edge or side*". This also proves that participants can distinguish between three basic shapes.



| | Square (1, 1) | Square (1.25, 0.75) | Square (0.75, 1.25) | Circle (1, 1) | Circle (1.25, 0.75) | Circle (0.75, 1.25) | Triangle (1, 1) | Triangle (1.25, 0.75) | Triangle (0.75, 1.25) |
|---|---|---|---|---|---|---|---|---|---|
| Square (1, 1) | 33.3 | 0 | 17 | 0 | 8.33 | 16.7 | 8.33 | 8.33 | 8.33 |
| Square (1.25, 0.75) | 16.7 | 33.3 | 0 | 0 | 8.33 | 0 | 8.33 | 8.33 | 25 |
| Square (0.75, 1.25) | 0 | 16.7 | 42 | 0 | 0 | 8.33 | 8.33 | 0 | 25 |
| Circle (1, 1) | 8.33 | 16.7 | 8.3 | 25 | 0 | 16.7 | 16.7 | 8.33 | 0 |
| Circle (1.25, 0.75) | 0 | 8.33 | 0 | 8.3 | 41.7 | 8.33 | 16.7 | 16.7 | 0 |
| Circle (0.75, 1.25) | 0 | 0 | 8.3 | 25 | 8.33 | 33.3 | 0 | 0 | 25 |
| Triangle (1, 1) | 0 | 8.33 | 0 | 0 | 8.33 | 0 | 25 | 25 | 33.3 |
| Triangle (1.25, 0.75) | 0 | 8.33 | 0 | 8.3 | 8.33 | 8.33 | 8.33 | 50 | 8.33 |
| Triangle (0.75, 1.25) | 0 | 0 | 8.3 | 17 | 8.33 | 0 | 8.33 | 0 | 58.3 |

**Figure 9: Confusion matrix showing the result of study 2.1.**



| | Square (1, 1) | Square (1.25, 0.75) | Square (0.75, 1.25) | Circle (1, 1) | Circle (1.25, 0.75) | Circle (0.75, 1.25) | Triangle (1, 1) | Triangle (1.25, 0.75) | Triangle (0.75, 1.25) |
|---|---|---|---|---|---|---|---|---|---|
| Square (1, 1) | 71.4 | 14.3 | 0 | 0 | 7.14 | 0 | 0 | 7.14 | 0 |
| Square (1.25, 0.75) | 7.14 | 64.3 | 0 | 7.1 | 14.3 | 0 | 0 | 7.14 | 0 |
| Square (0.75, 1.25) | 7.14 | 14.3 | 50 | 0 | 7.14 | 14.3 | 0 | 7.14 | 0 |
| Circle (1, 1) | 7.14 | 0 | 7.1 | 57 | 0 | 21.4 | 0 | 7.14 | 0 |
| Circle (1.25, 0.75) | 8.33 | 0 | 0 | 8.3 | 83.3 | 0 | 0 | 0 | 0 |
| Circle (0.75, 1.25) | 0 | 0 | 8.3 | 0 | 8.33 | 58.3 | 0 | 8.33 | 8.33 |
| Triangle (1, 1) | 0 | 0 | 0 | 0 | 0 | 14.3 | 57.1 | 21.4 | 7.14 |
| Triangle (1.25, 0.75) | 0 | 0 | 0 | 0 | 7.14 | 7.14 | 0 | 85.7 | 0 |
| Triangle (0.75, 1.25) | 0 | 0 | 7.1 | 14 | 0 | 7.14 | 0 | 14.3 | 57.1 |

**Figure 10: Confusion matrix showing the result of study 2.2. Comparing with the Figure 9, the percentage predicting correctly is much higher.**

## User Study 3: Rendering Stiffness

We intended to investigate whether our device can give realism in the perception of soft and hard objects.

**Table 2: Variable used in equation 1**

| Variable | Description |
|---|---|
| $v$ | Speed of tracker attached to the hand. |
| $d$ | Distance from the collision point. |
| $dif$ | Distortion of mesh from original position. |
| $sF$ | Elastic force (constant). We defined as 10 here. |
| $c$ | Damping force (constant). We defined as 5 here. |
| $t$ | time. |

*Participants.* There were 12 right-handed participants recruited (8 male and 4 female), ages 18 to 41 (mean = 28.3). Each participant received a $9 (¥1,000) Amazon gift card for their participation in the study. Note that all participants in user study 3 had done user study 2.2.

*Experimental Setup.* We used the same setup for the apparatus used in study 1 and 2 including HTC Vive HMD, controller, tracker and proposed device.

*Method.* We used two-alternative forced choice (2AFC) tasks. We prepared five patterns of angle representation of the device and five patterns of visual deformation.

We changed the angle presented by multiplying gain to the original angle calculated from our method. Five gains were tested: 0, 0.25, 0.5, 0.75, 1. Zero means the wings never opened even when the stick hit the object. One means that the presented angle is the angle calculated from our method. We did not test gains greater than 1 since we thought unnatural to present angles greater than an angle calculated from our method.

As for visual deformation, we deformed the cube at the collision point so that the cube seemed soft. We changed each mesh of the cube with the following calculation [11]:

$$(\frac{kv}{1 + 1000d^2} - dif \cdot sF \cdot \Delta t) \cdot (1 - c \cdot \Delta t) \cdot \Delta t \tag{1}$$

$k$ is the visual deformation parameter that was varied. We tested five patterns for $k$: 0, 0.25, 0.5, 0.75, and 1. Zero means there is no deformation. A larger $k$ corresponds to a larger deformation, which means the softer the cube is perceived. Other parameters in the equation 1 are described in table 2.

*Procedure.* Both a training and a testing session took place, and there was no time limitation for all trials. In both the training and testing sessions, a cube was shown in front of participants.

In the training session, the angle gain was 1 and no deformation occurred in the cube.

In the testing session, participants were asked to answer the question "*which is softer, the cube visually represented or the cube represented with the tactile feedback?*". Participants had to answer either of the two choices. All combinations of patterns were tested for three times in random order for a total of 75 samples.

*Results and Discussion.* Regarding the results of study 3, a cumulative normal distribution of the form was fitted

$$f(x) = 1 - \frac{1}{\sqrt{2\pi}\sigma}\int_{-\infty}^{x} \exp\frac{-(t-\mu)^2}{2\sigma^2}dt$$

with real numbers $\sigma$ and $\mu$. According to the point of subjective equality, where the possibility that participants answer the cube represented by the tactile stimulus is softer, is 50%. The angle gain, where participants feel that the tactile stimulus matches the visual representation, is 1.94, 0.391, 0.192, 0.161, 0.145 for visual deformation parameter 0, 0.25, 0.5, 0.75, 1 respectively. In the case of no visual deformation, the possibility that participants answered that the observed cube was harder is significantly high. This can be explained by the fact that participants put emphasis on visual cues and, since was no visual deformation, the participants perceive that the visual cube is absolutely hard. As for the angle gain of 0, meaning no sense of pressure, some participants chose the visual cube as being the softer one since they commented that "*it is difficult to compare nothing at all with a cube shown in VR space*". However, the result supports the notion that changing the gain of angle can render harder and softer material.

## 5 EXAMPLE APPLICATIONS

We built two applications to explore the possibility of using our device in various scenes.

*Whack-A-Mole.* The first application emphasizes the capabilities of our device to render shape and stiffness. From some of the holes in front of the user, moles appear randomly. The player can receive a score by hitting the moles with a pow hammer. Two kinds of moles appear in the game: moles with a helmet (hard) and moles with nothing (soft). At the end of the game, the boss mole emerged. As the user hits the boss mole, the boss mole gets a bump at the hitting point, which means the shape of the boss mole changes. As for soft materials, we used the parameter estimated from the result of study 3.

*Katana-Cutting.* This application highlights the size rendering and consecutive touching because we also expect our device can render consecutive touching. A player can cut a roll of straw with a Katana, or Japanese sword. A new roll of straw with a specific size appears randomly as the user cuts it. In this application, our device works in the same way as study 1 when the Katana hits the roll of straw. When the user is cutting, the virtual Katana shown in virtual space is delayed for 0.1 s and the angle between the virtual Katana and the hand-based Katana is represented as the angle at which the wings of the device are open. This means that the angle becomes bigger when the cutting speed is higher.

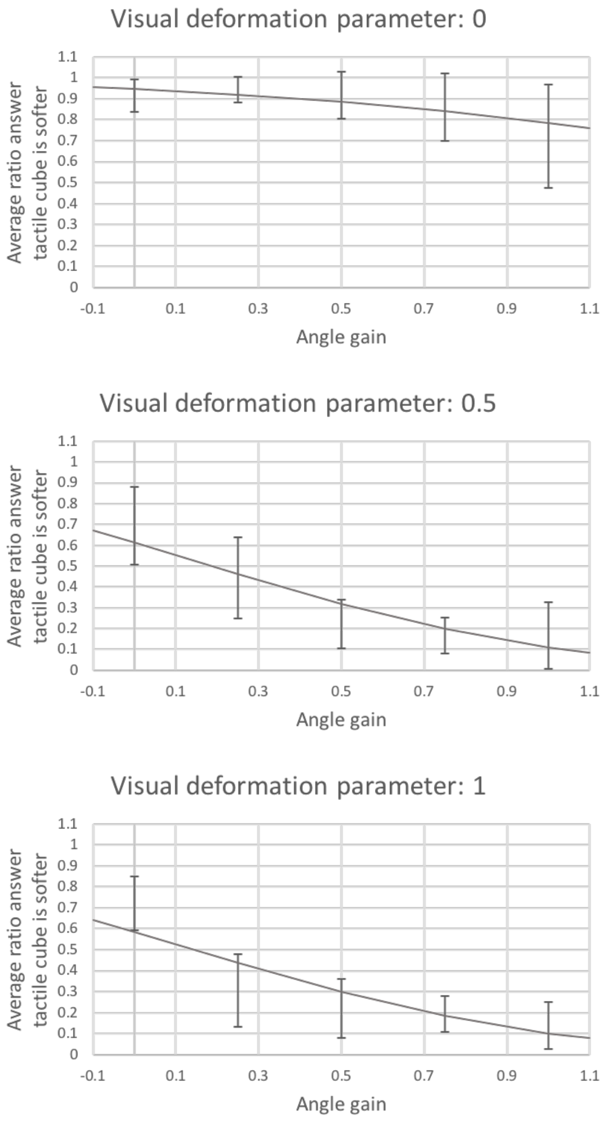


**Figure 11: Result of experiment 3 with the line fitted to cumulative normal distribution. Only the results with visual deformation parameter of 0, 0.5, 1 are presented. Error bars indicate 95% bootstrap confidence interval.**

### User Feedback

We recruited 10 people (8 male and 2 female), ages 20 to 41 (mean = 28.1) to provide feedback after using our device in example applications to allow for an understanding of our proposed system's performance. Each user received a

**Figure 12: (left) Whack-A-Mole application that highlights stiffness and shape. (right) When a user wields the stick in the same direction, the specific angle is presented when (a) soft / (b) hard mole is hit.**

**Figure 13: (left) Katana-Cutting application that highlights size and consecutive touching. (right) Rolls of straw of various sizes can be cut using a virtual Katana.**

$9 (¥1,000) Amazon gift card for their participation in the study. Users wore an HMD and held our device in their right hands with tracker put on. In this test, we attached one vibration motor on the back of both wings of the PaCaPa. Users tested a standard vibrotactile notification or sense of pressure with our device for both applications. The order of playing applications and tactile feedback was randomized.

During the trial, we conducted a semi-structured interview to collect direct comments. After each trial, we allowed the users to rate the experience using 7-point Likert scale for a question ("*How well did the haptic rendering match your visual impression of the scene?*") and allowed for additional comments in a questionnaire as optional.

*Results and Discussion.* Overall, users were pleased that they could get a sense of collision using PaCaPa. Many users remarked that they perceived a sense of hitting something hard when hitting a mole wearing helmet. Most users, including one user who has experienced in *Iaido*, the art of drawing the Japanese sword, were also surprised at the reality of the haptics when cutting the roll of straw. As for vibrotactile notifications, many users mentioned that it is a common sensation. P3 said "*this sensation just notifies me that I am hitting something*". Users also rated our device as being more realistic than vibrotactile in a qualitative rating after each trial. Wilcoxon signed-rank tests between the realism responses showed that the responses related to experiences with PaCaPa are significant for Whack-A-Mole ($Z = -2.22$, $p = 0.026$) and Katana-Cutting ($Z = -2.67$, $p = 0.007$).

This study revealed that the device can render more strongly perceived haptics in a shorter time. Many users remarked that the haptics rendered by our device were simply stronger. P3 remarked that in the Katana-cutting application, "*especially when I cut at a very fast speed, there were almost no haptics for the vibrotactile one, but the sense of pressure remained even after I finished cutting*". P4 said "*after I experienced the wing opening (PaCaPa), I felt dissatisfied (at the experience with the vibrotactile). The haptic is weak (for the vibrotactile one)*". P9 commented "*I feel the haptics made by this device are stronger, and a stronger tactile simply makes the application enjoyable*". This is because our device gives direct pressure on palms with a large open angle.

We also received some insights from users on our performance for three kinds of rendering in applications. As for size and shape, we received many comments that visual object size and shape matches haptic feedback. P3 mentioned "*I feel heavier when I am cutting a thicker roll of straw*". Furthermore, our device also succeeded in rendering the cutting off of various pieces of the object. P3 commented that "*I am impressed with the reality when I cut a small piece of straw from the roll*". As for the stiffness difference between the moles, most of them noticed it using our device. However, a few of them said the haptic of the collision was simply small when hitting the soft mole without the helmet.

This study also suggests some future improvements to our device. P4 mentioned that the "*opening angle of the wings is too big making it difficult for me to hold, maybe just because my hand is small*". This problem can be solved by designing hardware that is easy to hold in hand or has a reduced opening angle. Also, some users proposed using a combination of pressure and vibrotactile feedback. P3 noted that "*the haptic of vibrotactile gives me the feeling of cutting things with a chain saw*". P10 mentioned that "*I also get haptic when a piece that I have cut off falls onto my Katana. I think vibrotactile one is better for this*". In the situation where the tool vibrates or a light thing falls onto the tool for a moment, vibrotactile may better. Some users also commentted on the weight of the device. In both applications, the handheld tools are long, and the hitting objects are located at the edge of the tool. Users felt that the weight difference reduced the reality. This can be improved by adding weight to the edge of the device.

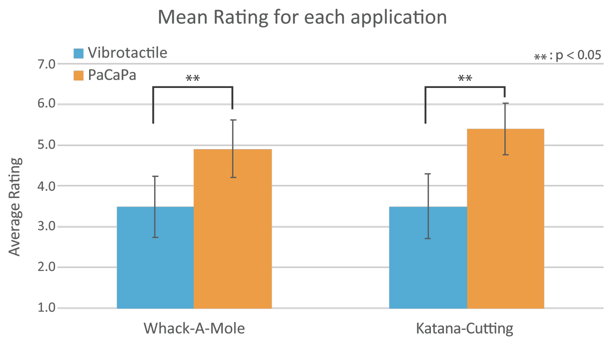


**Figure 14: Quantitative result showing mean realism rating. Error bars indicate 95% bootstrap confidence interval.**

## 6 LIMITATIONS AND FUTURE WORK

We designed PaCaPa with the intention of adding more realistic haptic feedback in tool-based interactions. We received many comments from the three studies as well as user feedback relating to example applications that mentioned how realistic it felt when hitting objects with a handheld tool. However, a few problems also arose that need to be solved in the future.

*Limitation in force direction.* Haptic presentation only comes from one direction in our design. This makes it impossible to accurately render the force direction. Increasing the size of the device and adding more servo motors can accomplish rendering in various directions. As the two wings open at the same angle, we could make the two wings be actuated with one servo motor, thereby creating greater torque. Then it is possible to create a device which can render two directions with the same size of the device. For practical use, it is ideal to make a device which can render any direction. Therefore, designing a device which can rotate to the position giving pressure can solve this problem.

*Perception delay of collision.* To render the pressure that comes from the limitation of the tool movement due to the object-tool collision, we calculated the angle between the hand direction and the virtual tool direction. Because of this software design, there was a delay in recognizing the collision especially when the user hit the object slowly as there is a threshold for recognizing the opening angle of the wings. Further accuracy can be achieved by adding vibrotactile feedback when the collision occurs.

*Wielding direction and size perception.* To achieve a better understanding regarding the use of our device, we need to explore the perception of size in tool-based interactions. Since we target tool-based interaction, there is a distance from the hand to the contact point. This makes it harder for the user to estimate actual size. In addition, some users mentioned that they felt different sizes for vertical and horizontal direction even if the size was the same. This suggests that we need to evaluate the size perception based on the wielding hand direction.

*Universal device for everyone.* Our device is not of a universal size to fit everyone. Some participants mentioned that the wings opened at too large an angle, making it difficult to hold the device. At the same time, some people could not place all fingers on the wing because of their hand being too big. This individual difference in hand size makes the haptic representation different. As future work, we need to make a larger device to give enough haptic feedback.

*Future work for general interaction.* We only evaluated the performance of our device in tool-based interaction. The results show that PaCaPa can emulate a stick-based tool. This leaves the problem of inaccuracy in the length perception and a limitation in terms of usage scenarios. However, since our device can work for tools of any length, theoretically it is possible to render direct interactions by placing the fingers on the wing. In this paper, we only tested opening the wings to the same angle at the same time. However, an open single wing can be used in this scenario. We need to make further evaluations in terms of this possibility. This broadens the possibility to render other properties such as texture. Testing results also indicate that our device can give the sense of tool-based interaction such as hitting and pushing with pressure. However, pressure is only one of the senses people perceive when they are interacting with objects. Because of the simplicity of our device, PaCaPa can be easily integrated with other devices such as Reactive Grip [23] giving shear forces to make the experience more realistic.

## 7 CONCLUSION

PaCaPa is a handheld device for tool-based interactions in the virtual environment. It demonstrates the potential to render three object properties, namely, size, shape and stiffness. We conducted user studies to evaluate the performance of our device on the rendering of these properties. Results from our evaluation validate that our device can render relative size, and participants can distinguish between basic shapes, and soft and hard objects. User comments from user studies and ratings in two applications show that PaCaPa can improve the haptic realism in tool-based interaction. We believe that our device, PaCaPa can offer a higher fidelity haptics experience in tool-based interactions.

## 8 ACKNOWLEDGEMENTS

We thank Ryunosuke Hirai for application development and Masato Nomiyama for video creation.

## REFERENCES

[1] Merwan Achibet, Maud Marchal, Ferran Argelaguet, and Anatole Lécuyer. 2014. The Virtual Mitten: A novel interaction paradigm for visuo-haptic manipulation of objects using grip force. In *3D User Interfaces (3DUI), 2014 IEEE Symposium on*. IEEE, 59–66.

[2] M Osama Alhalabi, Vytautas Daniulaitis, Haruhisa Kawasaki, Yuji Tanaka, and Takumi Hori. 2004. Haptic interaction rendering technique for HIRO: An opposite human hand haptic interface robot. In *Proceedings of EuroHaptics*, Vol. 459. 462.

[3] Tomohiro Amemiya, Hideyuki Ando, and Taro Maeda. 2008. Lead-me interface for a pulling sensation from hand-held devices. *ACM Transactions on Applied Perception (TAP)* 5, 3 (2008), 15.

[4] Hrvoje Benko, Christian Holz, Mike Sinclair, and Eyal Ofek. 2016. Normaltouch and texturetouch: High-fidelity 3d haptic shape rendering on handheld virtual reality controllers. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. ACM, 717–728.

[5] Mourad Bouzit, Grigore Burdea, George Popescu, and Rares Boian. 2002. The Rutgers Master II-new design force-feedback glove. *IEEE/ASME Transactions on mechatronics* 7, 2 (2002), 256–263.

[6] Tom Carter, Sue Ann Seah, Benjamin Long, Bruce Drinkwater, and Sriram Subramanian. 2013. UltraHaptics: multi-point mid-air haptic feedback for touch surfaces. In *Proceedings of the 26th annual ACM symposium on User interface software and technology*. ACM, 505–514.

[7] Li-Te Cheng, Rick Kazman, and John Robinson. 1997. Vibrotactile feedback in delicate virtual reality operations. In *Proceedings of the fourth ACM international conference on multimedia*. ACM, 243–251.

[8] Inrak Choi, Heather Culbertson, Mark R Miller, Alex Olwal, and Sean Follmer. 2017. Grabity: A Wearable Haptic Interface for Simulating Weight and Grasping in Virtual Reality. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology*. ACM, 119–130.

[9] Inrak Choi, Elliot W Hawkes, David L Christensen, Christopher J Ploch, and Sean Follmer. 2016. Wolverine: A wearable haptic interface for grasping in virtual reality. In *Intelligent Robots and Systems (IROS), 2016 IEEE/RSJ International Conference on*. IEEE, 986–993.

[10] Inrak Choi, Eyal Ofek, Hrvoje Benko, Mike Sinclair, and Christian Holz. 2018. CLAW: A Multifunctional Handheld Haptic Controller for Grasping, Touching, and Triggering in Virtual Reality. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, 654.

[11] Jasper Flick. 2018. Mesh Deformation, a Unity C# Tutorial. Retrieved Dec 21, 2018 from https://catlikecoding.com/unity/tutorials/mesh-deformation/

[12] Venkatraghavan Gourishankar, Govindarajan Srimathveeravalli, and Thenkurussi Kesavadas. 2007. Hapstick: a high fidelity haptic simulation for billiards. In *EuroHaptics Conference, 2007 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics 2007. Second Joint*. IEEE, 494–500.

[13] Xiaochi Gu, Yifei Zhang, Weize Sun, Yuanzhe Bian, Dao Zhou, and Per Ola Kristensson. 2016. Dexmo: An inexpensive and lightweight mechanical exoskeleton for motion capture and force feedback in VR. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. ACM, 1991–1995.

[14] Taku Hachisu, Michi Sato, Shogo Fukushima, and Hiroyuki Kajimoto. 2011. HaCHIStick: simulating haptic sensation on tablet pc for musical instruments application. In *Proceedings of the 24th annual ACM symposium adjunct on User interface software and technology*. ACM, 73–74.

[15] Koichi Hirota and Michitaka Hirose. 1998. Implementation of partial surface display. *Presence* 7, 6 (1998), 638–649.

[16] Yuki Imamura, Hironori Arakawa, Sho Kamuro, Kouta Minamizawa, and Susumu Tachi. 2011. HAPMAP: Haptic walking navigation system with support by the sense of handrail. In *ACM SIGGRAPH 2011 Emerging Technologies*. ACM, 6.

[17] Ginga Kato, Yoshihiro Kuroda, Ilana Nisky, Kiyoshi Kiyokawa, and Haruo Takemura. 2015. HapSticks: A novel method to present vertical forces in tool-mediated interactions by a non-grounded rotation mechanism. In *World Haptics Conference (WHC), 2015 IEEE*. IEEE, 400–407.

[18] Yoshio Kohno, Somsak Walairacht, Shoichi Hasegawa, Yasuharu Koike, and Makoto Sato. 2001. Evaluation of two-handed multi-finger haptic device SPIDAR-8. *ICAT2001* 12 (2001), 2001.

[19] G Michael Lemole Jr, P Pat Banerjee, Cristian Luciano, Sergey Neckrysh, and Fady T Charbel. 2007. Virtual reality in neurosurgical education: part-task ventriculostomy simulation with dynamic visual and haptic feedback. *Neurosurgery* 61, 1 (2007), 142–149.

[20] Benjamin C Mac Murray, Bryan N Peele, Patricia Xu, Josef Spjut, Omer Shapira, David Luebke, and Robert F Shepherd. 2018. A variable shape and variable stiffness controller for haptic virtual interactions. In *2018 IEEE International Conference on Soft Robotics (RoboSoft)*. IEEE, 264–269.

[21] Thomas H Massie, J Kenneth Salisbury, et al. 1994. The phantom haptic interface: A device for probing virtual objects. In *Proceedings of the ASME winter annual meeting, symposium on haptic interfaces for virtual environment and teleoperator systems*, Vol. 55. Citeseer, 295–300.

[22] Shuhei Nakagawara, Hiroyuki Kajimoto, Naoki Kawakami, Susumu Tachi, and Ichiro Kawabuchi. 2005. An encounter-type multi-fingered master hand using circuitous joints. In *Robotics and Automation, 2005. ICRA 2005. Proceedings of the 2005 IEEE International Conference on*. IEEE, 2667–2672.

[23] William Provancher. 2014. Creating greater VR immersion by emulating force feedback with ungrounded tactile feedback. *IQT Quarterly* 6, 2 (2014), 18–21.

[24] Samuel B Schorr and Allison M Okamura. 2017. Fingertip tactile devices for virtual object manipulation and exploration. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. ACM, 3115–3119.

[25] Chi Wang Chi-huang Chiang Da-Yuan Huang Liwei Chan Bing-Yu Chen Shan-Yuan Teng, Tzu-Sheng Kuo. 2018. PuPoP: Pop-up Prop on Palm for Virtual Reality. In *Proceedings of the 31th Annual Symposium on User Interface Software and Technology*. ACM.

[26] Alexa F Siu, Eric J Gonzalez, Shenli Yuan, Jason B Ginsberg, and Sean Follmer. 2018. shapeShift: 2D Spatial Manipulation and Self-Actuation of Tabletop Shape Displays for Tangible and Haptic Interaction. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, 291.

[27] CyberGlove Systems. [n. d.]. CyberGrasp. Retrieved Sep 18, 2018 from http://www.cyberglovesystems.com/cybergrasp/

[28] Dzmitry Tsetserukou, Katsunari Sato, and Susumu Tachi. 2010. ExoInterfaces: novel exosceleton haptic interfaces for virtual reality, augmented sport and rehabilitation. In *Proceedings of the 1st Augmented Human International Conference*. ACM, 1.

[29] Eric Whitmire, Hrvoje Benko, Christian Holz, Eyal Ofek, and Mike Sinclair. 2018. Haptic Revolver: Touch, Shear, Texture, and Shape Rendering on a Reconfigurable Virtual Reality Controller. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, 86.

[30] Kyle N Winfree, Jamie Gewirtz, Thomas Mather, Jonathan Fiene, and Katherine J Kuchenbecker. 2009. A high fidelity ungrounded torque feedback device: The iTorqU 2.0. In *EuroHaptics conference, 2009 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics 2009. Third Joint*. IEEE, 261–266.

[31] Kotaro Yamaguchi, Ginga Kato, Yoshihiro Kuroda, Kiyoshi Kiyokawa, and Haruo Takemura. 2016. A Non-grounded and Encountered-type

Haptic Display Using a Drone. In *Proceedings of the 2016 Symposium on Spatial User Interaction*. ACM, 43–46.

[32] Vibol Yem, Ryuta Okazaki, and Hiroyuki Kajimoto. 2016. FinGAR: combination of electrical and mechanical stimulation for high-fidelity tactile presentation. In *ACM SIGGRAPH 2016 Emerging Technologies*. ACM, 7.

[33] Andre Zenner and Antonio Krüger. 2017. Shifty: A Weight-Shifting Dynamic Passive Haptic Proxy to Enhance Object Perception in Virtual Reality. *IEEE Transactions on Visualization and Computer Graphics* 23, 4 (2017), 1285–1294.

[34] Craig B Zilles and J Kenneth Salisbury. 1995. A constraint-based god-object method for haptic display. In *Intelligent Robots and Systems 95.'Human Robot Interaction and Cooperative Robots', Proceedings. 1995 IEEE/RSJ International Conference on*, Vol. 3. IEEE, 146–151.