

EncounteredLimbs: A Room-scale Encountered-type Haptic Presentation using Wearable Robotic Arms

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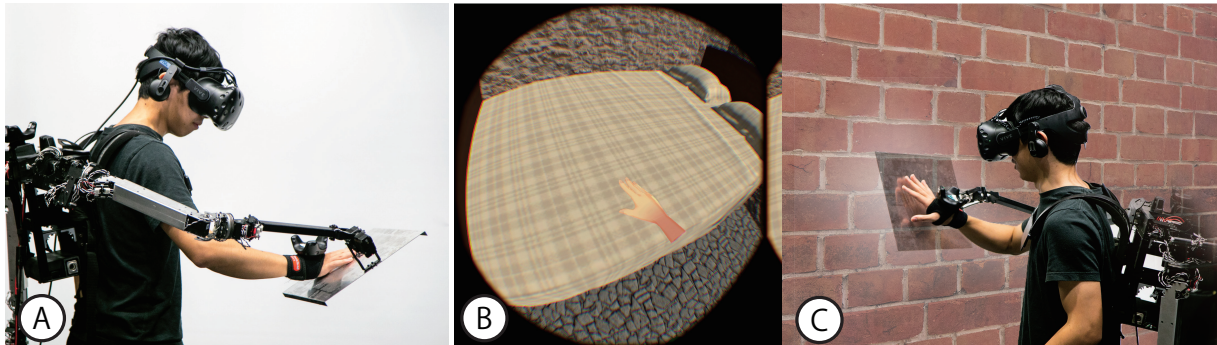


Figure 1: EncounteredLimbs overview:(A) Wearable robotic arm provides surface contact position and orientation of virtual objects for the user’s hand.(B) The user can touch objects in VR. (C) Mobility of the proposed system allows room-scale interaction.

ABSTRACT

Haptic information significantly improves human awareness of objects in virtual reality. One way of presenting this information is via encountered-type haptic feedback. An advantage of encounter type feedback is that it enables physical interaction with virtual environments without the need for specialized haptic devices on the hand. Additionally, encountered-type haptics are known for being able to provide high quality contact feedback to the user. However, such systems are typically designed to be grounded (i.e., fixed to the floor). As such, they typically have bounded workspace and a limited range of possible applications.

In this work, we present a novel, wearable approach to presenting a user with encountered-type haptic feedback. We realize this feedback using a wearable robotic limb that holds a plate where the user might interact with their environment. An appropriate location for the plate is determined by a novel haptic solver while control of the arm is made possible using motion trackers. The system was designed to be stable, for presenting consistent haptic feedback, while also being safe and lightweight for wearability. By making the feedback system wearable, we enable the presentation of stiff feedback while maintaining the spatial freedom and unbounded workspace of natural hand interaction.

Herein, we present the design of the novel system, mechanical and safety considerations when designing a wearable encountered-type system, and an evaluation of the system. A technical evaluation of the implemented system showed that the system provides a stiffness over 25 N/m and slant angle errors under 3°. Three user studies show the limitations of haptic slant perception in humans and the quantitative and qualitative effectiveness of the current prototype system. We conclude the paper by discussing various potential

applications and possible improvements that could be made to the system.

Index Terms: Human-centered computing—Human computer interaction(HCI)—Interaction devices—Haptic devices;

1 INTRODUCTION

Recent advances in the virtual reality (VR) field are thought to be due to the advent of head-mounted displays (HMD) that can present visual information in high quality. Such devices have delivered visual improvements in the virtual environment in both seated and room-scale scenarios. However, other stimuli are also important in increasing the realism of presence and immersion in VR. For example, the use of tactile, olfactory, and thermal feedback can significantly increase the sense of immersion in a virtual environment. When interacting with physical content, touch follows immediately after vision in terms of importance. It provides a rigid embodiment of objects and a clear understanding of their surface and materiality.

As with head-mounted displays, haptic interfaces must be immediately accessible and ubiquitous, so that they can deliver tactile information on demand. Many haptic devices realize this by presenting vibrotactile feedback or force feedback through electromechanically controlled gloves. These devices, however, often do not reliably replicate the materiality of the objects as they cannot render a realistic sense of collision. Furthermore, they usually result in a reduced sense of immersion due to the constant awareness of the worn interface (such as gloves). Many other methods, such as hand-held [11], mid-air [16], wearable-type haptic presentation systems [30], and tool-mediated stimulus [29] have been proposed in the fields of HCI and robotics, but they also struggle to render a realistic sense of collision. To date, only encountered-type haptics, where physical objects are dynamically positioned to emulate contact with virtual objects, have successfully replicated a reliable and highly realistic sense of collision.

Existing encountered-type haptic feedback systems use grounded robotic arms to deliver haptic stimuli to the user (typically their hand) via an object attached to the robot’s end-effector. Such haptic systems provide a high level of physicality to the user. However, due to their grounded nature, they have a bounded workspace and are often limited in the kinds of objects they can display. To resolve

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some of these issues, a variety of novel haptic interfaces have been proposed. One such approach uses drones [45] to deliver haptic presentation in midair [1, 2]. While this approach frees encountered-type haptic feedback from its workspace limitations, it has its own set of limitations (e.g., it cannot provide sufficient stiffness to create realistic haptic representations of objects in a virtual environment)

In this paper, we present a novel wearable, encountered-type haptic interface system that can deliver surface haptic sensation to the user in an unbounded workspace while maintaining a sense of immersion in the virtual environment. The system, *EncounteredLimbs*, achieves room-scale encountered-type haptic rendering by attaching robotic limbs with a flat end-effector to the user’s back as shown in Fig. 1. The system determines how to present the appropriate haptic feedback using motion tracking sensors and a haptic solver. The solver calculates the appropriate robot posture based on the user’s hand posture and nearby virtual objects. The robot arms weigh approximately 8 kg, and are comfortable to wear. Further details regarding the design of the system are presented in Section 3.

We evaluated the system’s specifications in terms of plate slant presentation accuracy and presentable force. The results showed that the system can present slant with an error under 3° and stiffness over 25 N/m. We also conducted a preliminary study on human slant perception using the method of constant stimuli. The results show that humans can discriminate the angle of a slant over about 5° . Two user studies evaluated the experience of using the system quantitatively and qualitatively. The first experiment investigated how well the system present a slant direction. The results show that if the angle is set to over 20° , users can clearly perceive the slant direction. The second experiment investigated how the system can improve a VR experience. The results show that users felt a significantly greater presence in VR environment when using the proposed system. Experiments and their results are described in further detail in Section 4 and 5.

The paper concludes with a discussion of the results obtained from the studies, future direction and other potential applications of *EncounteredLimbs*, and the limitations of the current prototype in Sections 6, 7, and 8, respectively.

1.1 Contributions

Here we summarize the main contributions of this paper:

1. Proposing a method for room-scale encountered-type haptic presentation using wearable robotic arms and considering robot and human posture.
2. Design considerations for overcoming the safety issues of using wearable robotic arms with limited visual information.
3. A psychophysical analysis of human perception of inclined wall in front of the user.
4. A user study reporting the qualitative effectiveness of the proposed system.

2 RELATED WORKS

Herein, we provide a review of encountered-type haptic interfaces with a focus on wearable systems. We additionally review the literature on wearable robotic limbs to provide background for our system design considerations.

2.1 Encountered-Type Haptics

Encountered-type haptic interfaces presents a physical object, usually attached to a robot end effector, such that it comes into contact with the user’s body when haptic feedback is needed [17, 25]. Such interfaces deliver the tactile forces when touch occurs, producing a near-perfect contact surface. These robot-based interfaces are usually grounded such that they can provide stiff feedback. While they provide high-quality haptic feedback, due to their grounded nature, they have a limited working space.

To address this issue, quadcopters [1, 2, 45] have been used as contact surface carriers to provide a larger working space. Using quadcopters, however, limits the rigidity and amount of force that can be presented. In addition, path planning for the drone becomes complicated when the user navigates in the workspace space. Recently, some researchers have proposed room-scale encountered-type haptic systems that use popup props [40], moving walls [6, 46], and mobile furniture [7] as an alternative. Though these systems provide rigid force presentation, the presentable orientation is restricted to the shape of the physical props and responsiveness of moving props are limited.

2.2 Wearable Encountered-Type Haptics for the Hands

Another approach that has been proposed to resolve the workspace-size issue of grounded encountered haptic systems is to make the systems wearable. With these wearable-Encountered-type haptic device, a mechanism is worn on the body and the end effector is brought into contact with the target site only during a contact event. For example, Nishimura et al. proposed a device that reproduces contact and friction with the central part of the finger pad [28]. Other works have proposed a wrist-worn device for replicating juggling [27] and virtual gripping experiences [20, 23]. While these systems can present contact events, they cannot restrict the arm’s movement because the area near the hand is the ground point, limiting the range of scenarios in which they might be applicable.

2.3 Wearable Robotic Limbs

Recent work in wearable robotic limbs has investigated attaching a high degree of freedom robot limbs to the body in an effort to enhance human capabilities. Some examples include, attaching an extra arm [31, 37, 38], leg [32], and even fingers [21, 34, 44] that can become a functional body part. In the early stages of the field, supernumerary robotic limbs were proposed for supporting manufacturing operations or body balancing [5, 31, 32]. The dexterity of these robotic limbs has since suggested new applications for wearable robotics. For example, these robotic limbs have been shown to be effective in new interaction areas, such as drum performance augmentation [18], telecollaboration platforms [36], and motor skill learning systems [22]

To realize these applications, wearable robotic arms typically have a high degree of freedom and sizable working space while being lightweight for wearability. There have been few trials suggesting that they could be used for active haptic feedback interfaces. HapticSerpent [3], for example, proposed a wearable link-based actuator system that provides haptic feedback on the torso, neck, face, arms, and hands. However, the system does not include a tracking system. As such, it does not allow for active touch interactions and haptic presentation based on the global position of the user and their relationship to objects placed in the virtual environment. This limits the applicability of the system. User hand tracking and manipulation based on virtual object surfaces’ orientation are essential to realizing VR experiences through the encountered-type haptic presentation using a wearable robotic limbs. As such, using wearable robotic limbs for encountered-type haptic feedback to the hands has not yet been explored and has a high potential for delivering reliable and high-force haptic feedback.

This paper presents *EncounterLimbs*, a wearable-encountered-type haptic interface that addresses some of the previously stated limitations of existing haptic interfaces. Namely, it resolves the issues of workspace scalability, wearability, and contact force feedback.

3 ENCOUNTERLIMBS SYSTEM DESIGN

The overall system is divided into three main elements:

1. **User Tracking:** The user’s hands and torso postures are captured using HTC Vive position and orientation trackers attached to their body. Posture data is then fed into the simulator.
2. **Haptic Solver:** The solver is responsible for almost all system functions. It first takes the user’s hand position and posture data and projects it into the virtual environment. Next, it selects the virtual surface closest to the hand as the touch area. The solver then uses an inverse kinematic model of the robot arms to calculate robot joint angles such that the physical touch surface presented by the arms matches the virtual touch surface. Finally, the simulator collects the current joint angles of the robot arms to visualize current end effector position for *safety guardian* described in 3.3.
3. **Robotic Arms:** The robot is equipped with two arms, each with 7-degrees of freedom and a surface plate mounted on its end effector. The robot arms receive joint angle data from the simulator target, and reports back its physical angles by reading the motor encoders values.

Here we will focus on the design details of the robotic arm and the haptic solver.

3.1 Robotic Arms Design

The developed robotic arms are shown in Fig. 2 with a user’s body presented as a reference. The arms we developed are based on the MetaArmS and Fusion designs [36, 37]. The mechanical design details are identical to these previous works. For the PID control system of the arms, an embedded microcontroller is used to drive the servo motors to the desired angles. This micro-controller receives the target angles via USB serial port connected to the PC which runs the Haptic Solver (Section 3.2). Adjustments were made to the design to fit our needs for the encountered haptic presentation (i.e., extending robot arm’s length to expand the working space). To generalize the use of the system for different body sizes and structures, We referred to the Digital Human Database [19] to determine the appropriate length of the arm links. System specifications such as the accuracy, precision, and presentable stiffness are provided in the technical evaluation section below.

Two different types of actuators were used, each with a different torque, speed, and weight are listed in Table 1. Overall, the actuators selected provide high torque and speed for their weight. The complete specifications of the arm joints (J1-J7) are listed in Table 2. The first two joints were designed to have a dual motor configuration such that their combined torque would be able to hold the arm in position when fully extended.

Each arm weighed approximately 2.5 kg, including the aluminum plate at the end effector. The backpack module that the user wears weight approximately 3 kg without the arms. Thus, the overall base

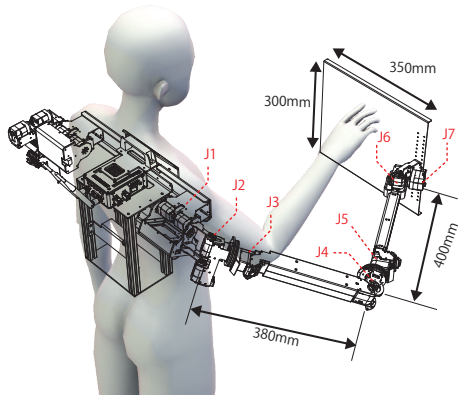


Figure 2: Structure and dimensions of EncounterLimbs robotic arms.

Table 1: Arms’ servomotors specifications.

Model	Torque	Speed	Weight
B3M-SC-1170-A	7.6N.m	0.21s/60°	105g
B3M-SC-1040-A	4.6N.m	0.18s/60°	82g

Table 2: Actuators specifications used for the design of the arms.

Joint	Actuator Type	Count	Min	Max
J1	B3M-SC-1170-A	Dual	-90°	80°
J2	B3M-SC-1171-A	Dual	-20°	90°
J3	B3M-SC-1172-A	Single	-90°	105°
J4	B3M-SC-1173-A	Single	0°	120°
J5	B3M-SC-1174-A	Single	-90°	90°
J6	B3M-SC-1040-A	Single	-80°	80°
J7	B3M-SC-1040-A	Single	-90°	90°

weight of the system was 8 kg. Power was supplied to the motors via a 12 V power supply with its output limited to 80 W for safety [12].

3.2 Haptic Solver

The solver calculates the target posture of the arms given the position of the user’s hand and the collision information presented in the virtual environment. The user hands’ position and orientation are tracked using HTC Vive trackers mounted on the back of the hand. One tracker is placed on the backpack module (where the robot arms are mounted) in order to construct the coordinate frame of the robot under the assumption that the robot shares the same coordinate system as the the user’s body.

A set of virtual rays originating from the hand are first used to determine a set of surface points near the virtual hand. The points selected are the first intersection point between the rays and a contact surface within a fixed distance from the virtual hand position. Fig. 3(A) shows these rays (green) and how points on the closest contact surface are selected. The position and orientation of the end-effector are determined by averaging the position and normal vector of the surfaces where the points are. The solver then calculates the inverse kinematics of the arms, and determines the motor angles needed to reproduce the surface position and angle on the end-effector (touch plate). The calculated angles are sent over the serial port to the arms’ micro-controller to drive the arms joints.

It should be noted that, since the desired end-effector position is determined relative to the hand position, sliding motions of the hand along a surface typically do not result in a tactile sensation of sliding. Instead, the end-effector follows the hand such that a sense of touch is preserved over the entire surface. This occurs both when the user is stationary and sliding his/her hand over a surface or while in motion with, for example, their hand on the wall.

3.3 Safety Considerations

Safety was one of the main priorities in the design of the system since the wearable nature of the system places the user within the workspace of the robotic arms at all times. Following safety guidelines defined for collaborative robots [12], the power of the robot was limited to 80 W and the speed of the end effector was limited, in software, to be at most 250 mm/s.

Since the user wears an HMD to visually perceive the virtual world, it is not possible for them to visually check where the robot arm is in the real world. Three safety measures are put in place to ensure the user’s safety in this situation. First, the edges of the end effector plate were covered with a soft material to avoid any sudden and hard collisions with the user’s hand or arm. Second, the robot PID parameters are tuned in order to achieve responsive position matching, while simultaneously having a velocity limit to avoid a high force impact with the user. Third, a collision surface was added around the virtual user’s body position such that the inverse kinematic model would attempt to avoid collisions with the human

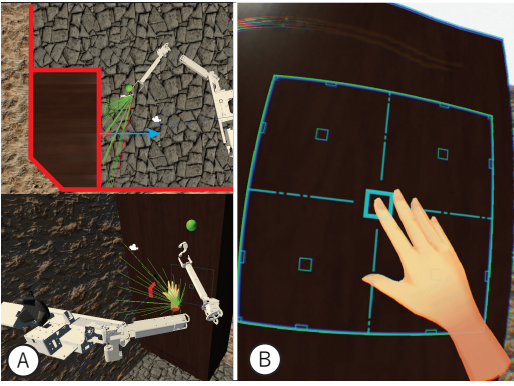


Figure 3: (A) Haptic solver predicting the contact surface location and orientation using an array of raycasts. (B) Visualized location of the estimated end effector's touch plate (also used as safety guardian).

Table 3: Accuracy and precision. Each cells shows the (μ, σ) average of recorded angles μ , and the standard deviations σ . The unit is $^\circ$.

	UP	DOWN	LEFT	RIGHT
10°	(8.2, 0.6)	(10.4, 0.5)	(10.3, 0.2)	(9.6, 0.3)
20°	(17.9, 1.1)	(21.1, 0.9)	(19.8, 0.8)	(21.8, 0.7)
30°	(27.6, 1.1)	(31.7, 0.5)	(30.4, 0.5)	(28.6, 0.8)

body when calculating a trajectory for the robot arms. Thus, even if the touch surface is located very close to the user's body, collision detection will ensure that the robotic arms will not unexpectedly hit the user's body.

Finally, an optional strategy, the *safety guardian*, was added to make the user aware of the robot end effector's location. The safety guardian provides a visualization of the position of the robot end effector in the virtual environment. As shown in Fig. 3(B), a virtual plane is rendered where the physical plate is located, and moves in tandem with the physical robot arm. Note that the *safety guardian* is applied only when the system is used with a VR application. As such, it is only activated in user study 2.

4 TECHNICAL EVALUATION

Since the robot arm used in the proposed system must be wearable, there is a trade-off between weight, accuracy, and deliverable torque. In this chapter, we examine the accuracy and hardness of the tactile feedback achieved by the proposed device.

4.1 Accuracy and precision

We measured the accuracy and precision of the presentation angle of the end-effector through several experiments presented in this section. In these experiments, the robot was fixed to the stand and a Vive Tracker was placed on top of the end effector as seen in Fig. 4(A). The angle of the end-effector placed in front of the person was tilted by 10° in each, direction up to 30°. The angle of the tracker in the stable state was recorded and repeated 10 times. Note that this was all done without the force sensor, also shown in Fig. 4(A), attached.

Table 3 shows the summary statistics (i.e., the means and standard deviations) of the measured angles. In all conditions, the difference between the desired and measured angles was less than 3° and the standard deviation was less than 2°. Although these values are significantly larger than those of grounded industrial robot arms, we believe that it is sufficient for roughly rendering wall slopes and large object shapes.

4.2 Presentable Stiffness

For encountered-type haptics, it is important to be able to present sufficient stiffness at the end-effector in order to convey the pres-

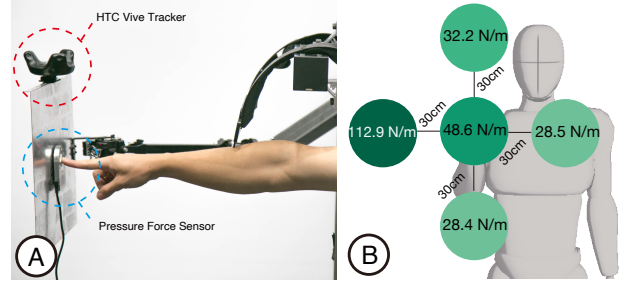


Figure 4: Stiffness calculation: (A) Evaluation setup and procedure, and (B) The evaluated locations with their corresponding calculated stiffness using the end-effector's displacement and applied force.

ence of physical objects. To evaluate the stiffness of the arms, we measured the displacement of the end-effector and applied normal force as shown in Fig. 4(A).

A HTC Vive tracker was attached to the end-effector to calculate its displacement, and a pressure sensor (Leprino 055YA501) was used to measure the applied force. The plate was moved to five different locations as shown in Fig. 4(B) in order to build a location-dependent stiffness map. For each location, a perpendicular touch force was applied to the pressure sensor until the plate's displacement was 50 mm. This was repeated several times and the values were averaged to obtain the values shown in Fig. 4(B). The stiffness varied between 28.4 N/m and 112.9 N/m. The variance is a result of the arm position affecting the torque applied to the joints of the arm when force was applied to the pressure sensor.

An approach making use of passive brakes, as in Wolverine [10] or Wireality [15], may reach a higher stiffness while maintaining a wearable weight. However, a passive braking mechanism would not be able to cope with a person moving while touching an object because the relative position can change dynamically. Therefore, we decided to adopt a robotic arm with a lightweight servomotor that can always move actively.

5 USER STUDIES

In this chapter, we present three experiments. The first experiment was a preliminary one, in which we investigated tactile perception of slant direction in humans by using a grounded encountered-type haptic presentation device. It should be noted that the device used in this preliminary experiment is not our proposed system, but one with significantly higher stiffness, precision, and accuracy. In the second experiment, the first user study, we investigated how well slant presentation is achieved using the proposed system. Namely, we measured whether users are able to perceive the slant direction of a surface presented by our system. In the third experiment, the second user study, we evaluated how the proposed system contributes to the sense of presence in a VR experience. Here, we compared the sense of presence felt during a VR experience with and without our system. In this last study, our system was used to support a VR experience which involved walking around a virtual environment while touching objects.

5.1 Preliminary Study: the Absolute Threshold of Slant Perception

While researchers have investigated slant perception through the fingers using force presentation device such as PHANToM [8, 14, 33, 43], human slant perception using palm has received little attention. We discovered past studies which have used palm inclination as a proxy for evaluating human perception of geographical inclination [13], but were unable to find works investigating the psychophysical properties of slant detection. Thus, we conducted

a preliminary experiment which investigated the psychophysical properties of slant angle direction perception using human hands to provide a benchmark against which we could evaluate our proposed device

The experiments were conducted using a stiff grounded device to evaluate human perception in ideal conditions. The experiment was based on the traditional constant stimulus method and revealed the absolute threshold of human slant perception through the hand in front of the body. We compare the results of this experiment with the results obtained in User Study 1 to discuss system performance in the next section.

5.1.1 Method

There were 12 participants (2 females and 10 males, ages ranging from 22 to 34 years of age) involved in this experiment.

The experimental setup consisted of an audio-visual blocking device, a grounded encounter plate mounted on servo motors, and a controller to answer the plate slant direction. Participants wore an HMD and noise-canceling headphones with white noise playing to block out visual and auditory cues. The grounded encounter plate used two servo motors (Kondo B3M-SC-1170-A) to slant the plate. The torque was sufficient for slanting the plate and the slant error was confirmed to be less than 1° using a bevel meter before the experiment. The participants grasped the controller which had buttons for each answering slant directions with their left hand.

The experiment was divided into two sessions, one for examining slant in the vertical direction and the other for slant in the horizontal direction. The conditions of slant angles were 0° to 10° in each direction in increments of 2.5° . The number of trials per condition was 20, so the total number of trials per session was 200.

Participants performed the experiment as follows. They were seated in a designated chair, had the experiment explained to them, put on the HMD and noise-canceling headphones, and grasped a controller with four directional buttons in their left hand. The HMD showed the current number of trials. In the absence of audiovisual cues, they touched the plate with their right hand. Then, when they had decided which direction to answer, they removed their hand from the plate and responded with the controller in their left hand. Participants were free to touch the plate within the plane as they wished, but were instructed not to touch the edges. During the experiment, we observed most participants sliding their hands on the surface. As this experiment used the 2 alternative forced choice task method, only the up and down directions were available in the vertical sessions, and only the left and right directions were available in the horizontal sessions. After completing 100 trials, participants were allowed a break, during which they could take off the HMD and the headphone. Participants were also allowed to take a break whenever they felt tired, though without taking off the HMD and the headphones. After the vertical sessions were completed, the horizontal sessions were conducted, the total number of trials was 400 trials. The experiment typically lasted about 40 minutes, including the breaks.

5.1.2 Result

The results obtained from the experiment are shown in Fig. 5. The percentages of responses answering "Up" and "Left" in each condition were plotted and fitted to a cumulative normal distribution curve. Negative angles represent downward and rightward inclinations. The just-noticeable-differences (JNDs) were predicted to be 4.6° in the vertical direction and 5.2° in the horizontal direction based on 25% and 75% points. The point of subjective equality (PSE) showed biases of about 0.7° vertically and 1.7° horizontally.

5.2 User Study 1: Slant Presentation

As a fundamental investigation, this experiment evaluated the performance of the proposed system in terms of the user experience.

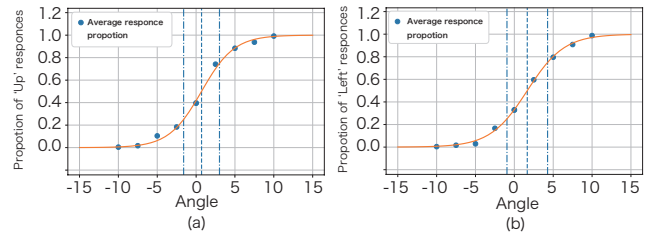


Figure 5: Dots show the proportion of the responses answering (a) "Up" or (b) "Left". The orange solid lines are sigmoid curves fitted to the data. The dashed vertical lines show the lower and upper thresholds and the point of subjective equality.

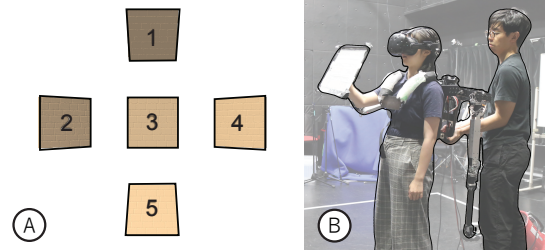


Figure 6: User Study 1 setup: (A) the five different surface orientations and answers used in the experiment. (B) A user actively touching the presented surface.

Namely, it focused on evaluating whether the system was able to have the user perceive the intended slant direction for a variety of slant angles.

5.2.1 Method

This study had 13 participants (3 females and 10 males, ranging in age from 18 to 24 years).

The stimuli used in this experiment were the five different wall directions shown in Fig. 6(A). For conditions other than condition 3, three types of stimuli with inclination angles of 10° , 20° , and 30° were prepared for each of the three sub-conditions, for a total of 12 conditions. Condition 3, which had no slant with respect to the body, had one sub-condition. For each participant, condition 3 had three trials and the other 12 conditions had one trial each for a total of 15 trials.

The participants started the experiment in an upright position with wearing the robot and HMD. At this stage, the robot was used to present the haptic stimulus while the HMD was left black so that the wall's state could not be estimated visually. Participants then touched the wall in front of them and estimated the direction. Participants were free to touch the plate within the plane, but were instructed not to touch the edges. Participants then verbally informed the operator when they had completed estimating the slant direction of the wall they had touched and were ready to answer. After the operator was notified, the answer choices were displayed on HMD as shown in Fig. 6(A). Participants answered the estimated wall orientation with the corresponding number, which the operator then recorded. This procedure was repeated 15 times.

For safety reasons, the operator waited next to the participants with an emergency stop switch in hand, as shown in Fig. 6(B). No time limit was set for answering the questions.

5.2.2 Result

The results of this study are shown as confusion matrices in Fig. 7. Cumulative results over all responses are presented in Fig. 7(A). The results for each slant angle magnitude, without condition Number

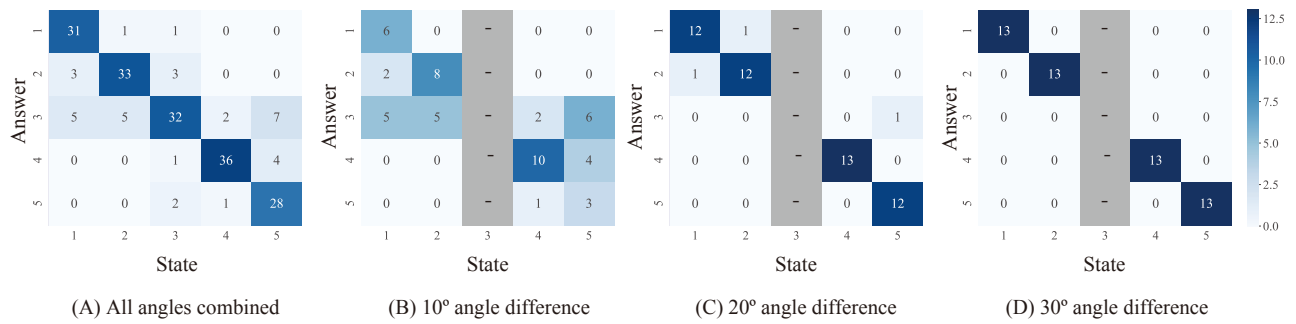


Figure 7: User Study 1 results: Inclined Direction Presentation. Confusion matrices for the tested states vs. answers.

3 (no slope¹) are shown in Fig. 7(B,C,D). By examining the the results for each slant angle magnitude, it can be seen that almost all of the trials are correct for the 20 and 30° trials. On the other hand, for the 10° trials, many participants reported that there was no slope.

5.3 Study 2: VR experience quality

This experiment focused on investigating whether EncounteredLimbs can be used to enhance the quality of presence during a VR experience.

5.3.1 Method

This study had 12 participants (3 females and 9 males, ages ranging from 18 to 24 years of age).

In this experiment, the user was allowed freely to explore a virtual environment. Exploration was conducted under two different conditions: with only visual stimulus and with both visual and haptic stimulus. The user wore an HMD in both conditions but only wore the EncounteredLimbs robot in the second condition. We chose to have the participants wear EncounteredLimbs in only one of the conditions as we wished to evaluate the net effect of wearing EncounteredLimbs. We assumed there existed a trade-off between the lack of immersion due to the weight of the robot and the presentation of tactile sensation. By having the participants wear the system in only one condition, we evaluated whether the proposed method results in a net positive effect on immersion. Each user experienced both conditions in a randomized order to eliminate ordinal effects.

The virtual environment was constructed to be approximately 3m x 3m. This size was chosen due to space limitations and tracking area limitations using the HTC Vive trackers. Note that the EncounteredLimbs itself has no spatial limitations and could be used in a much larger space given appropriate tracking systems.

Surfaces in the VR environment were arranged to have different surface inclinations (cabinet, walls, columns) and heights (e.g., the beds) to provide the opportunity to experience a variety of tactile surfaces. The room layout is shown in Fig. 8.

Exploration of the virtual environment began at a predetermined position, but participants were free to explore the environment as they wanted afterwards. The experiment ended after a certain amount of time (3 minutes on average) and all apparatuses were removed from their body. After each trial, the participants answered the questionnaire on a tablet device. For the questions, we adopted questions from the IPQ (igroup presence questionnaire) [39] that focused on "quality of presence":

- **G1:** In the computer-generated world, I had a sense of "being there" [Not at all–very much]
- **SP1:** Somehow, I felt that the virtual world surrounded me. [fully disagree–fully agree]
- **INV2:** I was not aware of my real environment. [fully disagree–fully agree]

¹Condition Number 3 represents zero angle (parallel to the user), thus it excluded from the last three figures.

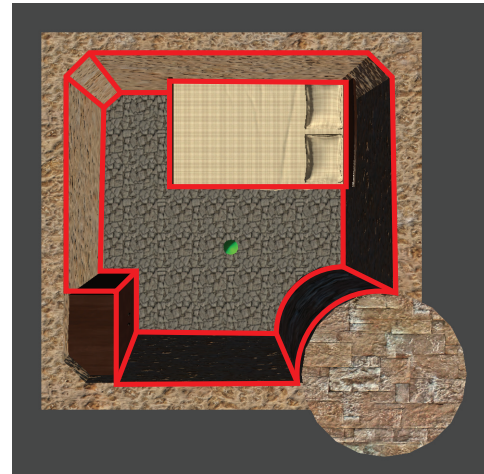


Figure 8: User Study 3 setup: The virtual environment used. The red lines outline the collision surfaces.

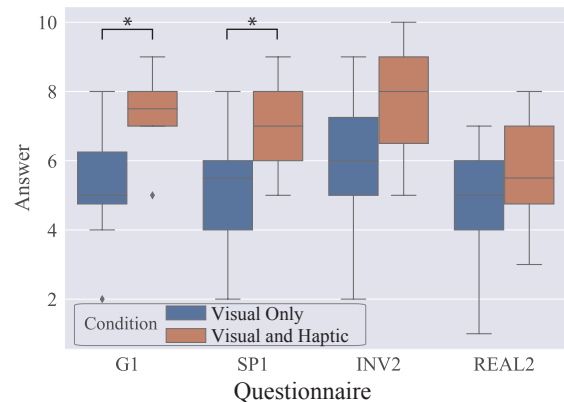


Figure 9: User Study 3 results: IPQ answers of each testing condition.

- **REAL2:** How much did your experience in the virtual environment seem consistent with your real-world experience? [inconsistent–moderately consistent–very consistent]

Once the responses were collected, the experiment moved on to the next trial. After all trials were completed, semi-structured interviews were conducted to obtain feedback on the experience.

5.3.2 Results

Results of the Questionnaire Fig. 9 shows user scores corresponding to each question for each condition. The whisker shows the range between the minimum and maximum values, and the box shows the lower and upper quartile. From the median value, we can

infer that the proposed method improved the user's sense of presence. This suggests that it has a positive effect on the VR experience. We conducted the Wilcoxon signed-rank test to determine whether the improvements were significant. Significant differences were observed in Item "G1" and "SP1" between visual and visual+haptics conditions ($p = 0.007$, $p = 0.03$).

Qualitative feedback from semi-structured interviews Almost all of the participants reported positive impressions of their experience with the system and reported that they enjoyed the VR experience. For example, P1 reported that, "*I knew the wall was presented by the robotic arm, but after the trial, when I took off the HMD, I felt an extraordinary feeling because there was actually no wall I touched.*" Similarly, P6 said, "*When there was only visual feedback, there was a lack of presence [of a wall].*" These comments suggest that the skin sensation presented by EncounteredLimbs enhances the sense of presence of the room. Several participants, including P5, P8, and P12 added that, "*It is so fun!*"

When we asked about the quality of the experience in more detail, most participants mentioned the quality of the moment of contact. P1, P4, and P5 reported "*The first time I touched it, I thought I was touching an actual wall.*"; P5 added, "*It is a very surprising experience.*" P9 said, "*I was able to try many orientations of touching with my palm. It increased the presence of the object.*" Furthermore, P3, P7, and P12 reported that, "*I could confirm the large shape of the objects.*"

In addition, participants pointed out possible improvements that could be made to improve the experience. For example, P2, P7, and P11 pointed out that, "*I felt the presence of actual objects, but their surface texture was always the same,*" and P3 and P5 said that "*The wall seemed to follow my hand when I try to stroke on the wall, it makes me feel strange.*" Furthermore, P8, P9, and P12 said, "*The vibration of the motor is sometimes annoying.*" P9 said, "*I could only touch with the palm and not with the other parts of the hand.*"

6 DISCUSSION

The preliminary study revealed a perception threshold for hand-based front-facing plate slant detection using an accurate grounded device. We observed that the JND of slant is about 5° in the forward facing orientation. A previous study shows that slant perception with fingers is about 3° in the horizontal orientation [33]. We assume that the reason for this difference is the reference orientation and way of touch. A bias in the PSE was observed in both the vertical and horizontal directions. The bias is thought to have been caused by the fact that the reference slope was presented only at the beginning of the experiment (i.e., due to there being no additional reference stimuli during trials). This would explain why the bias is especially prevalent in the horizontal trials. Since the chair's back is the only reference surface available, the bias is likely to occur more easily in the horizontal direction than the vertical.

The results of Experiment 1 suggest that participants can accurately recognize the direction of the slant presented by our system for slant angles of 20° or more. In contrast, the participants had trouble recognizing correct direction with the proposed system when the angle was 10° . This suggests that the JND of slant is between 10° and 20° . However, our preliminary study showed, with a stiff and reliable system, that the JND of slant is about 5° . The participants' inability to identify the slant direction at angles larger than 5° could be attributed to mechanical errors of at least 5° (to confuse the user at 10°). Again, however, independent evaluation of the system showed that the slant angle accuracy of the robot was measured to be within 3° of the true value. This suggests participants should be able to identify the slant direction at angles greater than 8° . We believe that other complications increased the difficulty of determining the slant direction to be greater than 10° . For example, accurate slant direction identification could be made more challenging by the plate position and orientation being disturbed by human motion during

the action of reaching out to touch the plate. It is believed that sufficiently accurate control of the arm and plate angles could improve the presentation of slant direction when using the proposed system.

In user study 2, it was observed that the proposed system had a positive impact on the VR experience. In the visual-only condition, the participants' hands passed through objects when they tried to touch them. In the tactile condition, such a phenomena did not occur. It is assumed that this difference made the users feel the presence of the object. As a result, they sensed that they were actually in the world, significantly improving their G1 score. The overall variance of the scores was larger because some participants had never worn an HMD before, and they may have been taken in by the novelty of the visual stimuli presented by the HMD.

In the semi-structured interview, many of the respondents clearly indicated that they felt they touched the wall, and it was evident that they had an increased sense of presence in the virtual environment. The significant improvement in the average SP1 score is thought to be due to the fact that the participants actively touched the wall multiple times, creating the experience of being surrounded by the wall. In fact, some participants moved beyond the virtual wall presented by the HMD in the visual-only condition, but no such behavior was observed in the tactile condition. According to the responses collected during the semi-structured interview, especially P1's comment, "*I knew the wall was presented by robotic arm, but after the trial, when I took off the HMD, I had a very extraordinary feeling because there was actually no wall I touched,*", it can be inferred that the system can strongly improve spatial presence, enough to induce the illusion of being in an enclosed environment. The reason why the REAL2 score did not improve significantly compared to the two above is likely due to the system's inability to fully represent realistic surface features of objects, such as texture and hardness. In the semi-structured interview, some participants mentioned the lack of varying surface textures and the sensation of the wall sliding with them. Since the system tracks the position of the hand and controls the position of the end-effector according to the position of the hand, sliding along a virtual wall will cause the wall to follow the hand. Since there is no relative displacement, there is no sensation of sliding the hand along the wall. This lack of a sense of slippage is thought to have reduced the sense of reality.

7 APPLICATIONS

Here, we summarize several ways in which our wearable robotic-arm based encountered haptic interface could be used in applications.

7.1 Room-Scale Surrounding Environment

As shown in User Study 2, it is possible to produce haptic feedback for a room-scale virtual environment with our system. By providing the boundary of the space with a wearable system, it is possible to perform free space design in software without having to build physical mockups. Users can freely touch objects in an enclosed environment and feel that they are interacting with them in a closed room. Since the proposed system is not limited to static surfaces, it could additionally be made to allow interactions with dynamic objects moving in space, producing changes in their motion. This makes the design of touch interactive VR environments feasible.

7.2 Redirected Walking

So far, redirected walking has been mainly performed with vision by gradually shifting the camera orientation to alter the user's walking direction [35]. However, other works have incorporated haptic feedback. The Unlimited corridor [24], for example, provided the perception of walking down an infinitely straight corridor, while the user actually walks in circles. The use of active touch on a static physical wall enhanced the redirection effect of the visual stimuli.

Using EncounterLimbs, it is possible to use a wearable encountered-type approach to achieve similar behavior. Since En-

counteredLimbs is not restricted in the same way fixed walls are, it could be used to quickly and easily enable touch enhanced redirection and the design other, more complex scenarios.

7.3 Virtual Guidance

Although this study only explored the use of a flat surface as haptic stimuli, the end effector can be easily redesigned to accommodate other types of feedback. For example, replacing the surface with a gripper would allow the creation of encountered-type hand grasping. Previous work [36] showed the potential of using long robotic arms to present the perception of being virtually pulled. Using a gripper on the end effector, it is possible to grasp and guide the user in a virtual environment, providing the illusion that they are being pulled along by a virtual character.

8 LIMITATIONS AND FUTURE WORK

8.1 Leaning against the wall

Proposed system does not allow the user to lean on virtual walls. As the system is grounded to the back, any and all forces exerted by the end-effector on the user's hand are equally and oppositely exerted on the user's back according to Newton's second law. As a result, the system is unable to exert any combination of forces which may result in a net displacement of the user (e.g., hold the user up if they to lean on a virtual wall). This is the same as not being able to pick oneself up by pulling at their own shirt. The system, therefore, provides the sensation of touching a wall (at the cost of feeling some pressure on the back), but cannot present a wall that can hold weight.

To overcome this problem with a wearable device, it is necessary to temporarily ground the device when an external force is needed. For example, for the device in our proposed system, if one of the two arms could be used to temporarily ground the system, the system could allow the user to lean against a virtual wall. Note, however, that the motors used in the current device described in this paper are unable to support such a large load. Future technological innovations will make it possible to achieve the temporarily grounding approach by using lightweight, high-torque actuators.

8.2 Limited Stiffness and Speed

Since this system is wearable, there is a limit to the weight, and therefore power, of the motor that can be used. Therefore, the system has a limited stiffness and may unintentionally move in some cases. For example, the system may be unable to withstand the inertia of the arm caused by the user's movement and the strong pressure of the user's hand on the touch surface. The limited output power of the motors also restricts the maximum speed at which the proposed system can move the touch surface. In addition, the overall speed of the robot was reduced for safety.

Solutions to these issues are expected come from taking visual retargeting and a pseudo-haptics approaches [9]. These methods are often used in encountered-type tactile presentations by drones due to their inability to present high forces. In these methods, the user is made to perceive that the robot is withstanding high forces even when it is not, thereby preserving the quality of the experience. Namely, these methods present a visual render of the user's virtual hand as if the robot was able to withstand the forces the user is placing on it. Since visual stimuli are typically more dominant than other stimuli, this can induce the illusion of the robot providing stiff feedback even when it is not. In addition, it is expected that this problem will be gradually solved by the emergence of lightweight and stronger motors in the future.

8.3 Sharp Corner Representation

It is difficult to present sharp corners with the proposed system. This is because the shape of the end effector is a flat plate and it always presents a planar stimulus.

To address this, it is possible to design an end effector with multiple shapes and features [41], or with a shape-changing interface (such as a inflatable effector [42]). Manipulating the end effector shape or orientation according to the touched surface will enhance the sense of tactile presentation.

In the user studies, only one arm of the robot was used to present stimulus. Both arms could be used in parallel to reproduce the sharp corners by changing how the plates touch each other.

8.4 Slip Sensation

Normally, when touching a wall-like surface in the real world, the surface is fixed, and relative displacement occurs when a human hand moves. However, currently, the way in which walls are presented using the proposed system causes the surface to move with the motion of the user's hand. Therefore, a slip sensation is not produced, which can reduce the sense of realism of a VR experience.

There is a possibility that this system can realize slip perception by a different end effector, such as using a belt conveyor [26] that produces a slipping sensation on the user's hand as they trace a wall. Another approach is to add vibrotactile feedback on the touch plate to induce a sense of surface texture and relative movement.

8.5 Texture Rendering

While the system described in this paper can present sensation of the position and orientation of large surfaces, it does not reproduce the tactile sensation of textures of objects. It is suspected that this is one reason why the evaluation of realism in User Study 2 was not high.

Encountered-type haptic feedback presentation has a great advantage for reproducing the sense of contact, but the experience it provides could be greatly improved by realizing texture reproduction. In previous work using grounded encountered haptics [4] and quadcopters [2], different textures were installed at the end effector, and the texture was rendered by precisely controlling the position of the end effector. Adopting a similar approach is likely to provide a more realistic experience with our proposed system.

9 CONCLUSION

In this paper, we proposed a novel wearable encountered-type haptic feedback presentation system called EncounteredLimbs. The design of this system was described and evaluated both quantitatively and qualitatively. To enable encountered-type haptic feedback presentation in a potentially unbounded work space, we developed a lightweight robot arm. The proposed system, when equipped with multiple tracking systems, estimates the position and orientation of the user's hand and controls the robot to position the end effector at an appropriate position, presenting tactile feedback which is in agreement with the virtual environment. A technical evaluation of this system showed that the error of the angle presentation is under 3°. The evaluation also showed that the stiffness the system can present varies with the location of the end effector, but that even the minimum stiffness was high enough to produce surface contact feedback. In a preliminary study, we determined that humans can recognize a surface's slant direction when it is inclined over approximately 5°. The user studies using the proposed system confirmed that the system can reliably have users perceive surface slant direction differences when the slant is at least 20°. Another user study showed that the system could cause a significant improvement in the sense of presence of a VR experience when used with visual feedback (in comparison to the visual feedback-only VR experience).

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