Body-Penetrating Tactile Phantom Sensations

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ABSTRACT
In tactile interaction, a phantom sensation refers to an illusion felt on the skin between two distant points at which vibrations are applied. It can improve the perceptual spatial resolution of tactile stimulation with a few tactors. All phantom sensations reported in the literature act on the skin or out of the body, but no such reports exist for those eliciting sensations penetrating the body. This paper addresses tactile phantom sensations in which two vibration actuators on the dorsal and palmar sides of the hand present an illusion of vibration passing through the hand. We also demonstrate similar tactile illusions for the torso. For optimal design, we conducted user studies while varying vibration frequency, envelope function, stimulus duration, and penetrating direction. Based on the results, we present design guidelines on penetrating phantom sensations for its use in immersive virtual reality applications.

Author Keywords
phantom sensation; tactile illusion; vibrotactile feedback; penetrating tactile sensation

CCS Concepts
•**Human-centered computing** → **Human computer interaction (HCI);** *User studies;* Haptic devices;

INTRODUCTION
The realism of haptic rendering is a key factor for presenting immersive experiences in Virtual Reality (VR). The best possible method at present is to use force-feedback devices to realize compelling haptic rendering of both kinesthetic and tactile sensory cues. However, such devices have limitations in size, weight, cost, and form factor and are still difficult to be used for a wide range of interactive applications. As an alternative, vibrotactile rendering has gained more popularity owing to its widespread availability and easy scalability [8]. In some cases, vibrotactile rendering has been elaborated to be able to substitute force rendering [43].

In general, vibrotactile rendering does not pursue the realism of experience but rather carves out unique tactile experiences.

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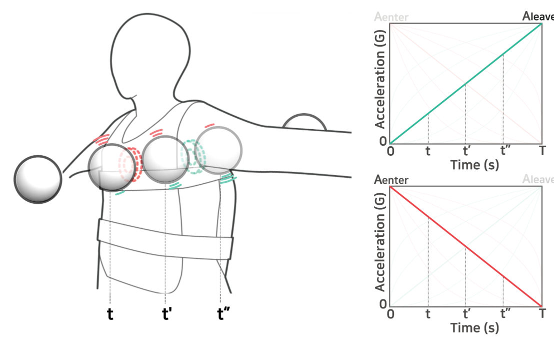

Figure 1. Concept of a tactile sensation passing through the body (torso). Only two vibration actuators are attached to the opposite locations on the ventral and dorsal sides of the torso. They present vibrations with the amplitude profiles shown in the two right plots. The amplitude on the entering side is initially the greatest and then gradually decreases. The amplitude profile on the leaving side has the opposite shape.

For example, one of the most popular vibrotactile rendering methods is using illusory tactile motion, such as phantom sensation, tactile apparent motion, and saltation. Such vibration rendering methods address the physicality of virtual environment by providing both discrete and continuous feedback for subsequent interactions in a relatively simple and efficient way [3, 17, 26, 27, 35, 37].

In this research, we focus on an untouched interaction area that the body *passes through* a virtual object after contact or a virtual object *penetrates* the body; see Figure 1. Although such penetration-related events are frequent in VR [24], methods to express them haptically have been largely disregarded, except for a few preliminary studies [32, 36, 48]. To physically render a penetrating tactile sensation, it requires a real stimulus that moves through the body. However, such invasive methods must be prohibited in VR. Instead, our approach is to utilize an illusory vibrotactile rendering method called *phantom sensation*. Here an illusory tactile sensation is felt between real actuation points, and the illusory sensation can be moved if the amplitudes of vibrations are temporally modulated. The perceptual performance of tactile phantom sensation rendering has been verified for many body sites and contact conditions [3, 17, 26, 27, 35, 37, 50].

For metaphoric expression of the sense of penetration, we elicit illusory moving tactile sensations using only two vibra-

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tion actuators placed on the opposite sides of a body part. For the body part, we focus on the hand and the torso as collisions with objects are frequent there in VR. For each body site, we conducted a user experiment to investigate whether a moving phantom sensation is perceived as if it passed through the body. The effects of potential factors, including envelope function, vibration frequency, stimulus duration, and penetrating direction, were extensively tested. For both body sites, the two most important factors were envelope function and vibration frequency. Generally, 100 Hz vibrations modulated by linear functions were rated as the best penetrating stimuli. The specific parameter values leading to the best penetrating tactile sensation depended on the conditions. Finally, we provide design guidelines for penetrating tactile illusions to help design immersive tactile experiences for broad applications in VR. To the literature, we add a new type of tactile phantom sensation that creates an illusory feeling for penetration.

RELATED WORK

Moving Phantom Sensation

According to the physiology research reported by Békésy [47], the human brain perceives two nearly synchronous vibrations in close spatial proximity as one stimulus from a single source. As a consequence, we perceive an illusory tactile sensation between the two real actuation points, which is known as *funneling illusion* or *phantom sensation*. In the early 1970s, a pioneering work by Alles [1] introduced tactile phantom sensation as an effective means to transmit non-audiovisual information to users. Using two vibrotactile pulses given to two points on the arm, he presented *stationary* phantom sensations. He also found that the logarithm profiles of vibration amplitude maintained evener perceptual strengths for the illusory sensations compared to the linear profiles. This work also shared many other fundamental observations as to the nature of phantom sensation. Recently, Berger et al. [3] demonstrated the human performance in localizing static phantom sensations in VR contexts. They found that presenting a congruent visual cue improves the perception of location by tactile illusion.

There have been many previous studies to make more expressive phantom sensations. In particular, researchers attempted to find the methods that continuously shift the perceived location of phantom sensation. Such moving tactile phantom sensation was verified for many instances: 1) with vibration actuators directly stimulating the skin [6], 2) within a physical medium that propagates vibration, e.g., a mobile device [20, 40], and 3) even outside the body with [22] and without [26] a physical medium. Interested readers may refer to the work of Park et al. [35] for a full taxonomy of tactile phantom sensations. Our work provides evidence that allow us to newly add a penetrating phantom sensation to Park's taxonomy.

To further elaborate the perceived quality of moving phantom sensations, researchers tried to find better vibration rendering profiles. Seo et al. designed general vibration synthesis functions using polynomials, tested many forms with different degrees of growth rate, and evaluated them for several quality metrics [41]. In [38], logarithm functions were preferred for expressing longitudinal motion between close actuators (3 cm apart) on the arm. Participants favored linear functions for the longitudinal motion between distant actuators (5–7 cm) and the transverse motion regardless of between-actuator distance. More complex amplitude functions, e.g., tangential [26], frequency sweep [20], and Gaussian [50], were also tested. Our experiments extensively and systematically modulated the amplitude envelopes of vibrations using polynomials, as in [41], in order to find optimal conditions for eliciting good passing-through tactile sensations.

Other previous efforts include 1) comparisons with other tactile rendering methods for moving sensations [27, 39], 2) extensions to two-dimensional surfaces [17, 22, 35, 42], and 3) applications to other body sites, e.g., the back of the torso [17, 50]. In particular, there is some evidence that phantom sensations better elicit moving tactile illusions compared to other methods for tactile motion. Raisamo et al. compared three stimulation methods for moving sensations—saltation, amplitude modulation, and their hybrid [39]. Participants generally preferred the amplitude-modulated phantom sensations. According to [27], phantom sensations better localize the tactile stimulus with a higher resolution than saltation-based methods. We found no direct comparisons between tactile apparent motion [17] and phantom sensation.

As stated in [17], there are no unifying theories that fully account for the illusory tactile sensations. The perceived quality of phantom sensations can be affected by unpredictable confounding factors such as contact site, vibration frequency, tactile motion direction, and stimulus duration. In this work, we explored tactile sensations that penetrate the body, which is another perpendicular axis to extend the dimensions of tactile rendering methods. We also included two body sites, hand and torso, to test for each penetrating direction, from dorsal to ventral and vice versa.

Vibrotactile Rendering for Interaction with Virtual Objects

Vibrotactile rendering has been evolved to provide unique and exceptional tactile experiences. In this section, we review vibrotactile rendering methods for two body sites, hand and torso, in the context of VR.

Hand

Moving tactile sensations support interaction by presenting artificial but unique tactile sensations onto the hand. Such vibration rendering methods include changing the perceived tactile location within fingers [26, 27] or a hand [35, 41], between the hands [3, 37], and even across two hands of different people [14]. These methods signify different events, such as localized tactile events [3, 27, 35], the movement of a virtual object [37, 41], pinching a virtual object [26], and the direction of interpersonal touch [14].

In this research, we focused on how to present the relativeness of the hand and virtual objects with a moving tactile illusion. We render tactile stimuli at the moment when the body makes contact with a virtual object, and then the tactile sensation moves to the position where the contact ends until the body comes out of the virtual object. The penetrating directions of stimuli were also tested to see how accurately users perceive the information. This tactile sensation provides informative feedback that implies two things about the relation between

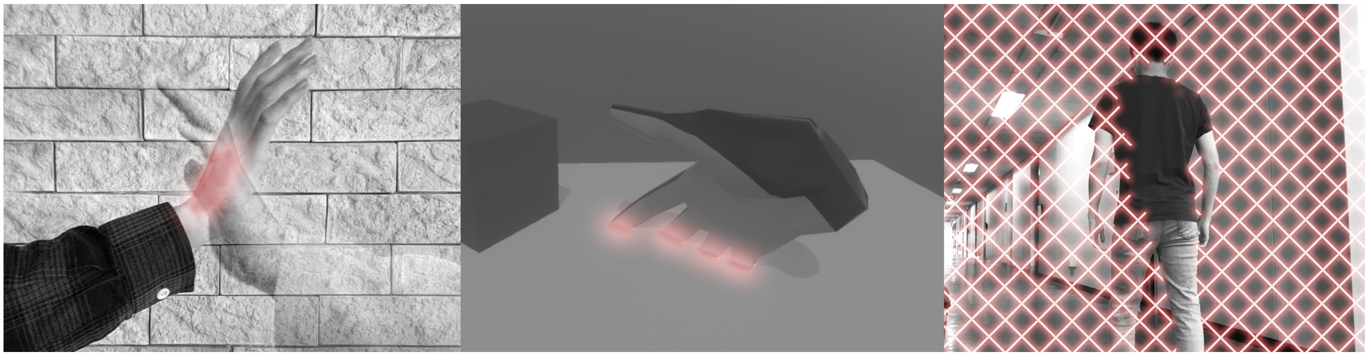

Figure 2. Examples where penetrating sensations can improve experience and usability in VR. The contact with the hand of a remote user in social interaction (Left). A user's hand penetrating a virtual surface (Middle). A user passing through a virtual wall or moving beyond a tracking area (Right).

the hand and object: 1) the direction of the motion and 2) and the relative position between them.

The spectral content of vibration plays an important role in its feel. Okamura et al. reported that rendering a decaying sinusoidal vibration with different frequency components reproduces the tactile feel of a real material [31]. This method is widely accepted in both academia [13, 33, 34] and industry [2]. Vibration frequency also changes the perceived size of virtual object [9]. In this work, we selected three frequencies, 40, 100, and 250 Hz, to express the diverse feels of virtual objects.

Torso

Vest and chair are the two most common form factors for displaying tactile sensations to the torso. The haptic vest has already gained popularity in industry [4, 10, 45, 46, 49] for gaming and entertainment. When compared to the hand, the torso is a less explored body site, but presenting tactile experiences to the torso has important potential for immersive VR experiences. There were preliminary studies about rendering sensations of being pierced on the body for gaming experiences [32, 48].

Researchers tried to enhance the expressiveness of tactile sensation to the torso [19, 23] or to design localized vibration on the torso [30]. Haptic experiences with a vest were systematically analyzed in [11], and thermal and tactile stimuli in the vest improve the immersion and presence. On the platform of chair, researchers improved VR experience using moving tactile sensations on the back [17] and the quality of moving tactile sensations applied to the posterior of the torso [50].

PENETRATING TACTILE SENSATION

Definitions and Implications

We define a penetrating tactile sensation as one that feels like passing through part of the body from one side to the other side. In real life, a penetrating sensation is not acceptable as it is mostly a pain. However, interaction in VR encounter many instances in which our body passes through or is passed by digital objects, such as grasping a virtual block and playing a first-person shooting game. Previous approaches to handle such instances include indicating collisions by vibrations [4, 25, 49] or visual effects [24]. Our goal is to provide a metaphoric, plausible, non-painful vibrotactile sensation that is experienced as moving through the body.

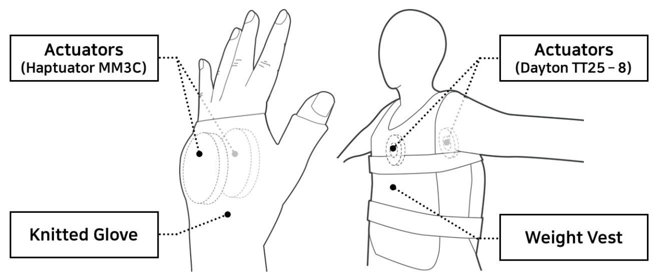

Figure 3. Schematic description of vibrotactile displays for hand (left) and torso (right).

Tactile rendering of the sense of penetration can present the direction of tactile sensation movement and the relative position between the two body surfaces. Such tactile sensation can be adopted to elicit a new dimension of tactile experience, such as the sense of presence, the existence of virtual entity, and the sense of self-motion or object motion. These primitive and groundbreaking tactile senses can provide 1) immersive experience in VR, e.g., users feel something invisible [28] or entertaining [17], and 2) valuable information about spatial interaction, e.g, leveraging the proprioception [43] and specifying the location and interaction possibility of user interfaces in VR (see Figure 2 and the accompanied video). To render penetrating tactile sensations, we selected to use moving illusory phantom sensations and investigated them thoroughly in this research. The following sections describe how we designed our system to verify the penetrating illusion.

Apparatus

We designed wearable vibrotactile displays for the two body sites of hand and torso (Figure 3). For the hand, we put two vibration units in a knitted glove. Each unit is in contact with the palmar and dorsal side of the hand, respectively. The two vibration units were adjusted to be in the centers of the palm and the back of the hand. The vibration unit had a voice coil actuator (Haptuator, MM3C HF) inside, which was enclosed by a 3D-printed cylinder-shaped cover (diameter 40 mm; height 13 mm). Each actuator was driven by a mono audio amplifier (Texas Instrument, TPA-6211A1EVM).

We selected a vest as the form factor to present vibrations to the torso. Two voice coil actuators (Dayton, Mini bass shaker TT25-8) with by stereo audio amplifiers (Bitway, A2) were placed on the front and back of the vest. They were located on the center of the sternum with two straps, which fastened the vest onto the torso.

Stimulus Characterization

In this research, we extensively explored the control space of moving phantom sensation to embody a penetrating illusion. We used three vibration frequencies (40, 100, and 250 Hz) to cover the entire range mediated by the two RA (rapidly adapting) mechanoreceptive neural channels. For this reason, we chose to use voice coil actuators that render a wide range of frequency, instead of more common LRA (Linear Resonance Actuator) or ERM (Eccentric Rotating Mass). The latter two have a limited frequency bandwidth or a dependency in frequency and amplitude, respectively [7].

We calibrated the two types of two voice coil actuators for the three vibration frequencies following the steps presented in [16]. The calibration was to identify the input-output relationships for our actuators, which ensures the replicability of results. We measured the output acceleration from each actuator using a high-precision piezoelectric accelerometer (Kistler, 8794A500, with a coupler 5134B) while changing the input amplitude. The measured acceleration in each condition was fit to a straight line without intercept for linear interpolation. The goodness of fit (R^2) for each actuator type was 0.975 ± 0.032 (the two actuators for hand) and 0.996 ± 0.007 (the two for torso).

Then, we proceeded to a series of psychophysical experiments to compensate for the sensitivity differences caused by vibration frequency and body site. In our method, vibrotactile stimuli are almost simultaneously presented to the palmar and dorsal sides of the hand (or the ventral and dorsal sides of the torso). Hence, it is essential to match the perceived intensities of vibrations at those opposite contact sites to render continuous and consistent penetrating tactile sensations. Also, it is a well-known fact that tactile sensitivity is contingent on vibration frequency [16, 18, 29], resulting in substantial differences in perceived intensity [15]. We asked seven participants (age 23 to 32 years) to match vibration amplitudes in the other conditions to the reference stimulus (6 G, 250 Hz; on the dorsal side of the hand) for the hand vibrotactile display, following the procedure of the method of adjustment. The same procedure was repeated to the torso with another reference stimulus (4.7 G, 250 Hz; at the ventral side of the torso). According to [1], actuation forces above 3 G are sufficient to stimulate marked tactile sensations. The stimulus duration was 1 second for all conditions. The measured data are shown in Figure 4 as equal sensation curves for each body site. The mean of each condition was used for the maximum amplitude of vibrotactile stimuli in Eq. (2) and (3) (see the next section).

Rendering Illusory Moving Phantom Sensation

In the literature, various amplitude modulation methods have been explored to elicit illusory moving tactile sensations. In this research, we parameterized the vibration amplitude with

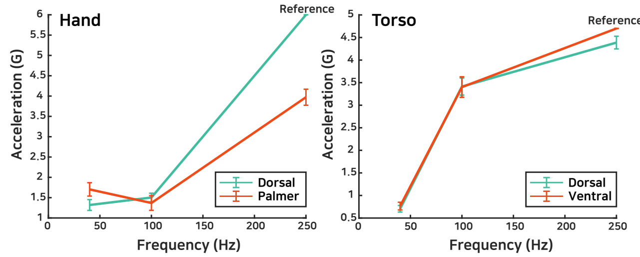

Figure 4. Equally perceived vibration amplitudes in acceleration for the two body sites. Error bars represent standard errors.

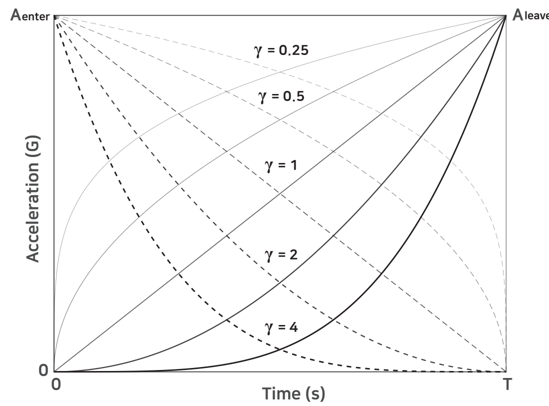

Figure 5. Modulation of vibration amplitudes for different degrees γ of polynomial. Dotted lines represent the amplitude of the actuator for entering stimulus $A_{enter}(freq, body)$. Solid lines are for $A_{leave}(freq, body)$.

the degree of polynomial (γ) as was done in [41] to systematically cover diverse functions for rendering penetrating tactile sensations. Changing the degree of polynomial produces various mathematical functions, including those similar to log and exponential profiles (see Figure 5).

The actuator i displays a vibration signal $x_i(t)$:

$$x_i(t) = a_i(t)\sin(2\pi F t), \quad (1)$$

where F is the vibration frequency and $a_i(t)$ is the amplitude of the i th actuator.

For two actuators across each body site, their amplitudes $a_i(t)$ were modulated by the following equations:

$$a_{enter}(t) = A_{enter}(freq, body)\left(1 - \frac{t}{T}\right)^{\gamma}, \quad (2)$$

$$a_{leave}(t) = A_{leave}(freq, body)\left(\frac{t}{T}\right), \quad (3)$$

where $A_i(freq, body)$ is from the equal sensation amplitudes in Figure 4, γ is a control parameter for vibration amplitude modulation, and T is the duration of tactile stimuli. i is decided by where a collision event starts.

EXPERIMENT 1: HAND

In this section, we report an experiment conducted to define the design space of illusory moving phantom sensations that pass through the hand. All experiments in this research were conducted under the protocols approved by the Institutional Review Board at the authors' institution.

Methods

Participants

We recruited 20 participants (10 males and 10 females; age 18 to 25 years) for this experiment. All participants were right-handed. None of them reported any known sensorimotor disorder. The participants were paid approximately USD 20 after the experiment.

Experiment Conditions

In this experiment, we used a four-factor within-subject factorial design. The four independent variables are *the degree of amplitude function* (***Gamma***; 0.25, 0.5, 1, 2, and 4), *the frequency of vibration* (***Frequency***; 40, 100, and 250 Hz), *the duration of stimulus* (***Duration***; 0.5 and 1.0 s), and *the direction of penetration* (***Direction***; from palmar to dorsal and vice versa). ***Gamma*** determines the speed of modulation, and its range was selected after pilot experiments. Using values outside the range do not render distinguishable phantom sensations. In the literature of tactile phantom sensations [1, 41], it was often reported that using a logarithmic profile for amplitude modulation results in a smoother and continuous sensation than a linear profile. In our case, $\gamma = 0.5$ gives the profile most similar to the logarithmic. The values for ***Frequency*** were chosen for a low frequency (40 Hz) mainly mediated by the RA 1 neural channel and a high frequency (250 Hz) by the PC (Pacinian) channel, as well as one (100 Hz) at the boundary. The two ***Duration*** values represent the durations of general collision-related events in VR applications.

We completely randomized ***Gamma***, ***Frequency***, and ***Duration*** to minimize the learning and order effect. The presentation of ***Direction*** was counter-balanced within the other factors. Participants repeated the 60 experimental conditions ($5 \times 3 \times 2 \times 2$) three times each. Each repetition was blocked, and only the results from the last two repetitions (blocks) were analyzed. Each participant conducted a total of 180 trials for this experiment.

Measures

To assess the feel of passing-through tactile sensation, we designed three evaluation measures. We assumed that a phantom sensation moving across the opposite sides of a single body part evokes a *passing-through* or *penetrating* tactile sensation if the tactile rendering method successfully elicits an *illusory* sensation in the body. Also, such an illusory tactile sensation is more expressive when the moving direction of tactile stimulus is clearly perceived. Therefore, we directly asked if the illusory tactile sensation feels like penetrating the body (PENETRATION) and if the direction of such a tactile sensation is clearly perceived (DIRECTION CLARITY). For these two questions, we reminded participants to focus only on the tactile sensation and ignore the visual information. Lastly, we questioned whether the tactile sensation is well matched to the visual information (HARMONY).

Task and Procedure

Prior to the experiment, participants read written instructions, and the experimenter verbally explained them again. After that, we asked participants to wear the vibrotactile display in their non-dominant hand (Figure 3). The experimental setup included a monitor and a numeric keypad (Figure 6, left). We implemented a VR scene that displayed graphical models for a hand and a virtual ball, graphical user interface (GUI) for rating, and descriptions about the measures (Figure 6). Participants wore noise cancelling headphones to block the sound emanating the actuators and the environmental noise.

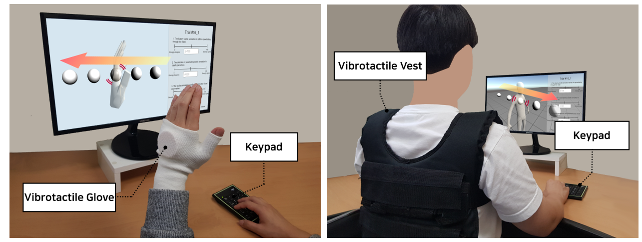

Figure 6. Experiment setup for hand (left) and torso (right).

To start each trial, participants pressed the asterisk key on the numeric keypad. Then the plain white ball, similar to a ping pong ball (diameter 3.95 cm), was moved toward the virtual hand, and vibrotactile stimuli for phantom sensation were initiated when a collision between the hand and ball was detected. The stimulus presentation was continued until the ball completely passed through the transparent virtual hand. Participants were not allowed to move or to change their hand pose during the presentation. They could experience the stimuli as many times as they wanted.

After the experience, we asked participants to rate the sensations of the stimuli for the three evaluation measures by typing numbers using the numeric keypad with their dominant hands. The range of numeric ratings were from 0 to 100, and the GUI also showed the meanings of extremes and a midpoint for each measure. Since participants were unfamiliar with illusory tactile sensations, they performed three repetitions for the same stimuli in different blocks. The first repetition was regarded as training to be exposed to all rendering conditions and to be familiar with the illusory sensations. Participants had a five minute break between the blocks of trials to prevent fatigue and sensory adaptation. The experiment took 60 to 110 minutes, including instruction time and breaks, per participant.

Results

For statistical tests, we applied four-way repeated measures ANOVA for each of the three measures of PENETRATION, DIRECTION CLARITY, and HARMONY. The direction of penetration ***Direction*** was not significant for any measure. For simplicity, we pooled the data of different ***Direction*** values and show the mean scores of the three measures in Figure 7 for the three vibration frequencies and the two durations. For each measure, the best condition is marked for each combination of frequency and duration with its value. We provide more detailed analysis results for each measure below.

Penetration

The highest scores for the feel of penetration ranged from 67.3 to 74.8 for the six conditions of vibration frequency

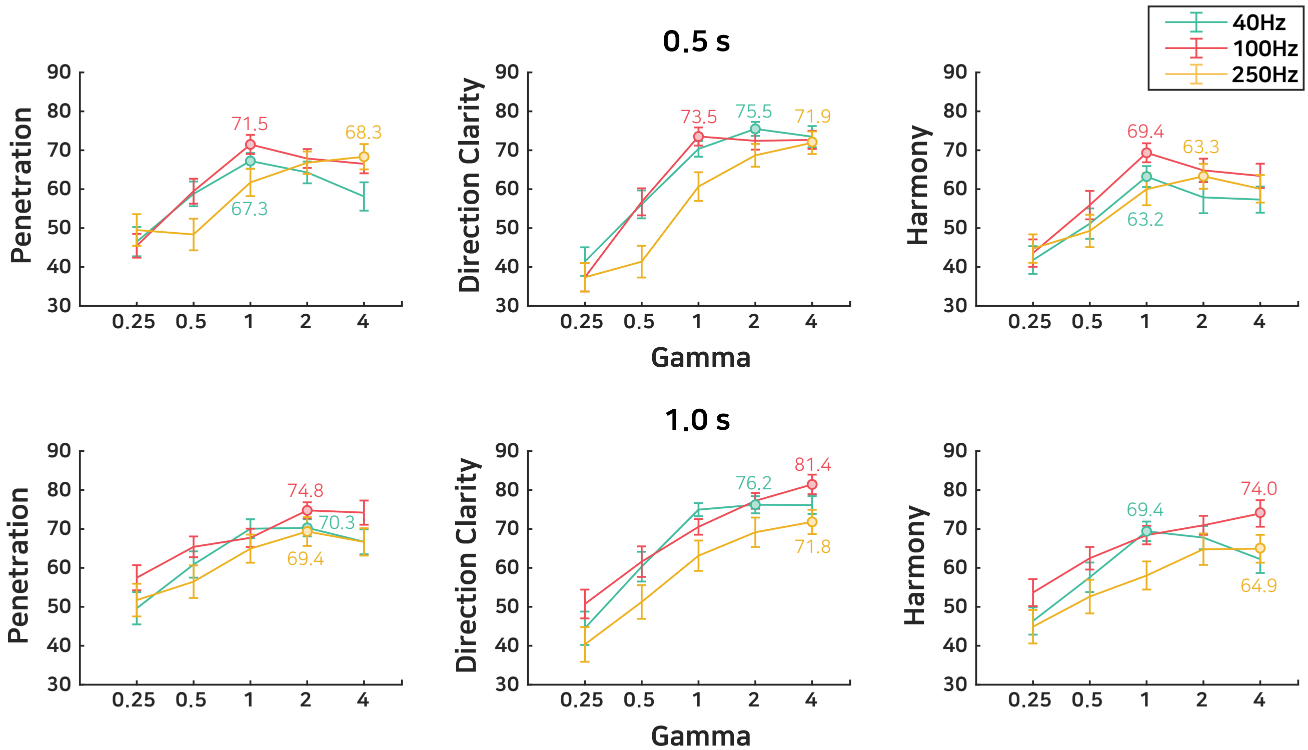

Figure 7. Mean scores for PENETRATION, DIRECTION CLARITY, and HARMONY measured in Experiment 1 for the hand. The condition that achieved the best score is indicated by a circle and the score on each graph.

and duration. These numbers can be regarded as quite high considering the general regression bias[1] of human scaling [12].

From the four-way repeated measures ANOVA, the main effects of modulation function (***Gamma***; $F(4,76) = 14.32, p < .000$) and stimulus duration (***Duration***; $F(1,19) = 6.15, p = .026$) on PENETRATION were significant. The other main effects of vibration frequency ***Frequency*** and penetration direction ***Direction*** were insignificant. Further inspection on the interaction terms revealed that the interaction between ***Gamma*** × ***Frequency*** ($F(8,152) = 2.07, p = .049$) was significant. For the higher order interactions, only ***Gamma*** × ***Frequency*** × ***Duration*** ($F(8,152) = 2.00, p = .050$) was significant.

Therefore, we observed two-way interaction at each level of ***Duration*** to unlock the entangled effects from the higher-order interaction. If ***Duration*** was 0.5 second, ***Gamma*** ($F(4,76) = 11.28, p < .000$) and the interaction between ***Gamma*** and ***Frequency*** ($F(8,152) = 3.28, p = .001$) were significant. Looking at the corresponding plot in Figure 7, the mean PENETRATION scores for 40 and 100 Hz were the highest at the middle ($\gamma = 1$). However, the PENETRATION scores for 250 Hz stimuli generally kept increasing with γ. For ***Duration*** of 1.0 second, the only significant factor was ***Gamma*** ($F(4,76) = 12.80, p < .000$). Regardless of ***Frequency***, the PENETRATION scores were the highest when $\gamma = 2$. However, we found no significantly different pairs between the linear ($\gamma = 1$) and perceptually slow-growing modulations ($\gamma = 2$ and 4).

In summary, the illusory feel of passing through is improved for longer stimuli. It can be maximized by choosing an appropriate amplitude modulation rate, γ in our case. The best value for γ depends on vibration frequency and duration, but using linear or larger values ($\gamma \geq 1$) is advantageous.

Direction Clarity

The highest scores for each condition of duration and frequency were between 71.8 and 81.4, as shown in Figure 7. Therefore, our method for rendering moving phantom sensations seem to be quite effective in delivering the intended direction of motion.

The four-way repeated measures ANOVA conducted for the DIRECTION CLARITY scores found three significant main factors of ***Gamma***, ***Frequency***, and ***Duration*** ($F(4,76) = 39.02, p < .000$; $F(2,38) = 3.41, p = .043$; $F(1,19) = 5.60, p = .029$). Larger ***Gamma*** generally increased DIRECTION CLARITY, regardless of the stimulus duration. For frequency, the mean DIRECTION CLARITY scores for 250 Hz stimuli tended to be lower than for the other two conditions. For clarification, we conducted pairwise comparisons by a Tukey's HSD test. The results showed that the 250 Hz conditions had a significantly lower mean score than the 100 Hz conditions, but no significant difference between 250 and 40 Hz (also 100 and 40 Hz).

[1] A response bias referring to participants' tendency of avoiding extreme responses.

When the stimulus duration ***Duration*** increased from 0.5 to 1.0 second, the mean DIRECTION CLARITY score increased by only 3.98. An interesting pattern about stimulus duration is found for 100 Hz. In the 0.5 second data, the trend of 100 Hz data followed that of 40 Hz data, but in the 1.0 second data, the trends of 100 and 250 Hz data were similar. This tendency was also observed in the results of the PENETRATION scores.

Harmony

The trends of HARMONY were very similar to those observed for PENETRATION (Figure 7), with similar statistical results. Its best scores were reasonably high, ranging from 63.2 to 74.0, for the six conditions of vibration frequency and duration. ***Gamma*** ($F(4,76) = 18.67, p < .000$) and ***Duration*** ($F(1,19) = 7.83, p = .011$) were the only significant main effects. Significant higher-order interaction was observed with only a four-way interaction term, but we leave its analysis out because of the complexity.

Participants rated the illusory sensation of the longer stimulus duration better accorded with the visual information. In each stimulus duration, the highest harmony score was observed in the 100 Hz conditions. The best modulation function for each duration was linear ($\gamma = 1$ for 0.5 s) and the slowest ($\gamma = 4$ for 1.0 s). In all conditions, the means of the HARMONY score increased until the degree of modulation became 1. For $\gamma \geq 1$, the trends were distinct between the frequencies and durations, but without statistically significant differences due to γ.

Discussion

This experiment investigated how to elicit illusory tactile sensations that cross the hand. Figure 9 presents scatter plots for DIRECTION CLARITY vs. PENETRATION for the three independent variables of frequency, duration, and γ. The plots visualize the positive and negative influences of the control factors for penetrating phantom sensations. It appears that the control space well covered the optimal conditions for use in the final design of penetrating illusion.

We extensively tested the amplitude profiles of vibration by varying their degree γ of polynomial. Increasing γ slows down the perceived rate of vibration amplitude growth, while decreasing γ makes it faster. Also, we examined the three representative frequencies that innervate the two different mechanoreceptor groups (Meissner and Pacinian corpuscles) [18, 16], which results in considerably different subjective feels [13, 21, 33, 34]. In addition, the conditions to test the effects of stimulus direction and duration were included.

As expected, the modulation functions represented by ***Gamma*** most significantly influenced the experience of sensory illusion. The fast-growing modulation ($\gamma = 0.25$ and 0.5) were not the best option for the penetrating illusion. This is against the literature of phantom sensations *on* the skin that generally preferred the logarithmic profile for its smooth and continuous feel [1, 41]. For our case of passing through the hand, the sensation evoked by the fast-growing modulation felt like both actuators vibrate almost simultaneously. A similar experience was reported by [17] for very short inter-stimulus onset asynchrony. As the modulation became slower, from $\gamma = 1$ to 4, all the three subjective measures were apt to improve. Sometimes the scores were best at $\gamma = 1$ or 2, or saturated. The slow-growing modulation presents a better contrast between the vibration stimuli at the event of entering and leaving (see Figure 5).

The stimulus duration ***Duration*** was also an important factor. Increasing the stimulus duration improved all subjective ratings of the illusory sensation with statistical significance. We also found that the trend of the 100 Hz conditions depended on the stimulus duration. For 0.5 second, the ratings of the 100 Hz conditions followed those of the 40 Hz conditions; see the red and green lines in the top panels of Figure 7. For 1.0 second, the 100 Hz data were similar to the 250 Hz data; the red and yellow lines in the bottom panels of Figure 7. These interesting observations are beneficial for handling frequency and duration if there are constraints on these parameters.

About ***Frequency***, the stimulus frequency had effects on the three measures, but they were not as salient as the other two independent variables. The 250 Hz stimuli generally had lower ratings than the 40 and 100 Hz stimuli, but the differences were not always significant.

Lastly, we did not find any meaningful effect as to the stimulus direction ***Direction***. This finding implies that our penetrating tactile sensations can be used to illustrate either leaving or entering virtual objects for the hand. Recall that we had equalized the perceived intensities of the stimuli at the different stimulation points (and also for the three frequencies).

EXPERIMENT 2: TORSO

As the second experiment, we tested penetrating sensation rendering for the torso. The two experiments had essentially the same design, except for the body site.

Methods

We recruited another 20 participants (10 males and 10 females; age 18 to 28 years) for this experiment. None of them reported any known sensorimotor disorder. No participant took part in Experiment 1. They were paid USD 15 after the experiment.

Figure 6 (right) shows the experimental setup for the torso. Participants wore the vibrotactile vest instead of the glove. The VR scene presented a transparent body from a front-right viewing angle where the perspective is fixed throughout the experiment. A white sphere passed through the torso, and it had approximately the size of a handball ball (diameter 17 cm).

Results

We ran a four-way repeated measures ANOVA for each subjective measure and found that the stimulus duration ***Duration*** was not significant for any measure. Thus, we present in Figure 8 the mean scores of the three measures from the pooled data of the two durations. This time all graphs had a shape of inverted U with the best scores at $\gamma = 1$ or 2.

Penetration

For the torso, the range of the best PENETRATION scores was between 57.1 and 76.1. The best scores were obtained with the linear modulation $\gamma = 1$, except for the 250 Hz, ventral-to-dorsal condition.

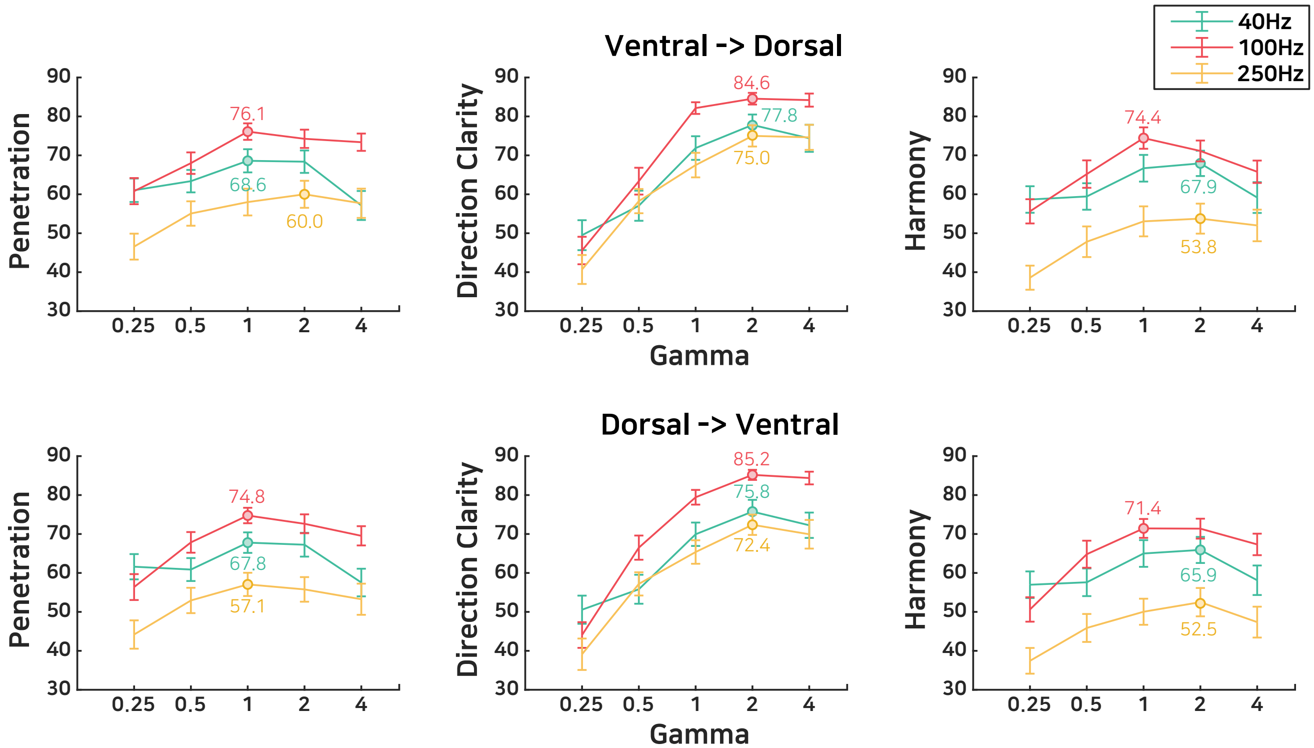

Figure 8. Mean scores for the three subjective measures collected in Experiment 2 for the torso.

The significant main effects were ***Gamma*** $(F(4,76) = 5.44, p = .000)$, ***Frequency*** $(F(2,38) = 7.62, p = .002)$, and ***Direction*** $(F(1,19) = 7.91, p = .011)$. Although the main effect of penetrating direction was significant unlike the results for the hand, the mean score difference between the two directions was only 1.93. Further, no noticeable differences were caused by ***Direction*** in the patterns of graphs in Figure 8.

The penetration scores of the 100 Hz conditions were higher than those of the 250 Hz conditions at all ***Gamma*** levels. A pairwise comparison by a Tukey's HSD test showed that the mean penetration score of the 250 Hz conditions was lower than that of 100 Hz with statistical significance. We found no other significant pairs by the vibration frequency.

The two-way interaction between ***Gamma*** and ***Frequency*** was significant $(F(8,152) = 3.49, p = .001)$, but no other higher-order interactions were. We conducted a simple effect analysis, and ***Gamma*** was certainly significant factor for each ***Frequency***. A pairwise comparison by a Tukey's HSD test was conducted whenever needed, and we report only significant comparisons. For 40 Hz, the PENETRATION scores for $\gamma = 1$ and 2 were significantly higher than the lowest score from $\gamma = 4$. For 100 Hz, the highest penetration score was found with $\gamma = 1$, which was significantly higher than the lowest scores from $\gamma = 0.25$ and 0.5. No significant differences were observed in the 250 Hz data. As it did in the hand, 100 Hz was generally the best frequency to elicit passing-through sensations.

Direction Clarity

The mean scores of DIRECTION CLARITY had the best values between 72.4 and 85.2. Here the stimulus duration ***Duration*** $(F(1,19) = 0.70, p = .413)$ and the penetration direction ***Direction*** $(F(1,19) = 3.39, p = .081)$ were not significant. The only significant effects were with the rate of modulation ***Gamma*** $(F(4,76) = 35.18, p < .000)$ and the vibration frequency ***Frequency*** $(F(2,38) = 4.21, p = .022)$, and their interaction $(F(8,152) = 3.40, p = .001)$.

The mean clarity scores of the 100 Hz conditions were higher than those of the other two frequency conditions when $\gamma \geq 0.5$ (Figure 8). For all vibration frequencies and penetration directions, the penetrating sensation presented by $\gamma = 2$ resulted in the highest clarity score. However, no significant differences were found between the modulation functions of $\gamma = 1$, 2, and 4, except between $\gamma = 1$ and 2 for 40 Hz.

Harmony

The highest scores for HARMONY were between 52.5 and 74.4. Like the hand, the HARMONY scores were also very correlated with the PENETRATION scores for the torso. Like PENETRATION, statistical significance for HARMONY was found with ***Gamma*** $(F(4,76) = 10.69, p < .000)$, ***Frequency*** $(F(2,38) = 9.96, p < .000)$, ***Direction*** $(F(1,19) = 6.11, p = .023)$, and ***Gamma*** $\times$ ***Frequency*** $(F(8,152) = 2.48, p = .015)$. In pairwise comparisons, the mean harmony scores of both 40 and 100 Hz conditions were significantly higher than for the 250 Hz condition.

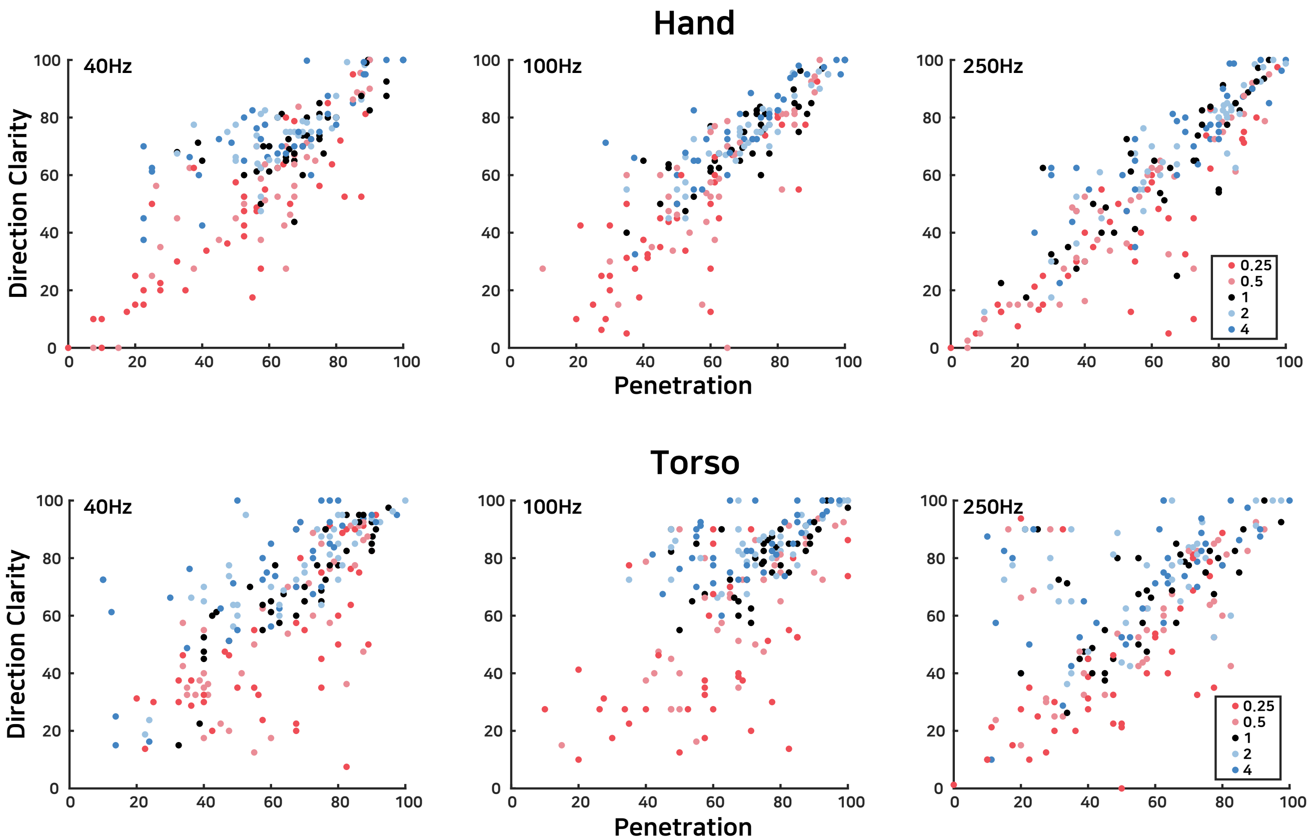

Figure 9. Scatter plot for DIRECTION CLARITY vs. PENETRATION and for each *Body* (rows) and *Frequency* (columns). In each plot, *Gamma* is encoded with color: 0.25 (red), 0.5 (light red), 1 (black), 2 (light blue), and 4 (blue).

Discussion

In this experiment, we continued the investigation on penetrating phantom sensations for another body site, the torso. Figure 9 shows the distributions of PENETRATION and DIRECTION CLARITY for the torso (and hand). If we compare the plots for the two body sites, the results for the torso are more scattered, suggesting that the effects of the independent factors were more apparent. Full comparisons between the two body parts are provided in the General Discussion section.

For penetrating phantom sensations to the torso, ***Gamma*** and ***Frequency*** were the two most significant factors. As the case of hand, penetrating tactile sensations rendered by fast-growing modulation ($\gamma = 0.25$ and 0.5) were not effective for any frequency. Using a higher γ is recommended. For the torso, the best penetrating experience was achieved by the linearly modulated 100 Hz stimuli where the penetration feel is clear without losing the sense of penetrating direction. For the 40 Hz stimuli, either linear or slowly-growing profiles delivered good passing-through sensations. The tactile experience from the 250 Hz stimuli was not as good as for the other frequencies. We suspect that such weaker tactile experiences are associated with the propagation of vibration through the skin. The transimissibility of vibration is lowered as the frequency of vibration increases [9]. This effect might be more significant in the torso (hairy skin) compared to the hand (glabrous skin) because mechanoreceptors (Pacinian and Meissner corpuscles) are much less populated on the torso [5].

The effects of the other two factors (***Duration*** and ***Direction***) were not substantial. Unlike the hand, the duration of stimulus was not significant. This may also stem from the worse vibrotactile discriminability on the torso compared to the hand [8], which includes the aforementioned reasons. Actually, the lack of meaningful differences between the two penetrating directions improves the practical applicability of penetrating phantom sensations.

GENERAL DISCUSSION

Comparison between Hand and Torso

In this section, we present comparisons between the results for the two body sites. We are allowed to run a statistical analysis owing to the identical experimental conditions. We conducted a five-factor mixed-design ANOVA (Between: ***Body***; Within: ***Gamma***, ***Freq***, ***Dur***, and ***Dir***) for all three subjective measures. We review only the between-subject factor here. Only DIRECTION CLARITY scores ($F(1,1140) = 19.29, p < .000$) were significantly affected by the body site, but the other two measures were not: PENETRATION ($F(1,1140) = .001, p = .972$)

and HARMONY ($F(1,1140) = 0.187, p = .665$). The direction of penetrating sensation was more clearly perceived on the torso (M 66.5) than the hand (M 62.6).

We can also make useful observations from a scatter plot in Figure 9 for DIRECTION CLARITY vs PENETRATION. HARMONY is excluded due to its similarity to PENETRATION. A good phantom sensation for penetration is one with high scores in both PENETRATION and DIRECTION CLARITY, i.e., those in the top-right corners in each plot. For both body sites, 100 Hz stimuli modulated by the linear ($\gamma = 1$; black) and slowly growing modulation functions ($\gamma = 2$; light blue) were closely distributed around the top-right corner. In the torso, the data from for $\gamma = 2$ were somewhat off the diagonal line. These agree with our findings that the linear function is recommended for the torso regardless of the stimulus duration, whereas in the hand the linear function for the short stimulus and $\gamma = 2$ for the long stimulus should be preferred.

As the data goes off the diagonal to the top-left corner, they represent the sensations that clearly notify the direction but do not feel like penetrating. This trend frequently appeared when $\gamma = 2$ and 4 (light blue and blue) at 40 and 250 Hz. In contrast, the data distributed in the bottom-right corners felt like penetrating but had high ambiguity in the direction perception. These stimuli might feel like almost simultaneously buzzing since they had only low γ values (0.25 and 0.5). All in all, the data should not go off the diagonal line of the perceptual space between PENETRATION and DIRECTION CLARITY.

During the experiment, we presented the movement of a virtual object in conjunction with tactile stimuli. This might have influenced the participants' ratings for PENETRATION and DIRECTION CLARITY although they were asked consider only the tactile experience. It could have affected their ratings on whether the visual and tactile stimuli are harmonious to be less independent of the other two metrics, resulting in HARMONY highly correlated with PENETRATION.

Design Considerations

Finally, we suggest design guidelines as to tactile phantom sensations that feel like penetrating.

1. We do not need to care for penetrating direction to design good penetrating phantom sensations on the hand or torso.
2. We expect that stimulus duration is decided by other events. For the hand, the duration should have higher priority when deciding control factors; we found reasonable differences in the subjective ratings between the tested duration (0.5 and 1 s). We did not find such differences in the torso.
3. Since vibration frequency determines the feel, matching the properties of a virtual object and the frequency can improve the tactile experience. According to [33, 44], a higher frequency can be a good selection for metallic virtual objects, and lower frequencies around 40 Hz feel like rumbling or bumpy. Among the three vibration frequencies we tested, illusory penetrating sensations are elicited most effectively with 100 Hz at both body sites. All other body site-frequency pairs presented decent penetrating tactile illusion, but 250 Hz is not recommended for the torso.
4. After the major variables listed above are determined, one can choose a modulation function that presents the best penetrating tactile sensation. From our observations, a high degree γ of polynomial generally provides good penetrating tactile sensations with clearly perceived passing-through direction; beyond some point, however, the tactile sensation might not feel like penetrating but two discrete vibrations.

CONCLUSIONS

We have explored the presentation of simulated tactile sensation appropriate for a virtual object passing through part of the human body. To elicit such a moving illusory sensation, vibrotactile phantom sensation is exploited. Through a series of perceptual experiments, we extensively investigated the parameters of phantom sensation that stimulates the hand and torso as if the tactile sensation penetrated the body site. Our empirical findings from the experiments can improve the quality of tactile rendering by providing ways to render more expressive tactile sensations. We also provide design guidelines for eliciting good penetrating tactile sensations while handling constraints on stimulus frequency and duration, and contact site.

Our control space extensively covers the parameters of penetrating phantom sensation. There are still other parameters that may further improve the tactile experience, such as controlling the amplitude of vibration and using multiple actuators on each side of the body. Future work may also consider comparison with other tactile modalities, e.g., thermal, or a combination with other modalities, e.g., vibro-thermal and vibro-auditory. Finally, we will further study the effectiveness of rendering passing-through illusions when a user conducts bare-hand manual tasks, e.g., finding an object of interest in VR and rendering the virtual ends of a motion tracking space.

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