2023 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)

2023 IEEE International Symposium on Mixed and Augmented Reality (ISMAR) | 979-8-3503-2838-7/23/$31.00 ©2023 IEEE | DOI: 10.1109/ISMAR59233.2023.00119

Expansion of Detection Thresholds for Hand Redirection using Noisy Tendon Electrical Stimulation

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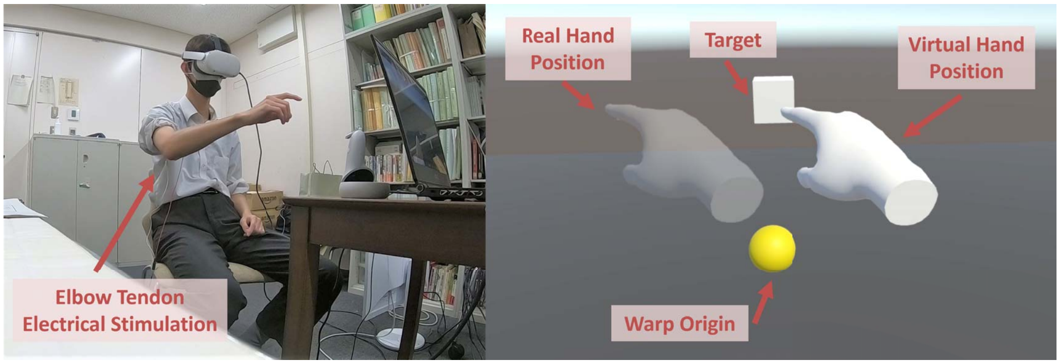

Figure 1: Hand redirection with noisy tendon electrical stimulation. Participants wore electrodes around the elbow of the right arm, and were exposed to weak, noisy electric stimulation during reaching tasks. In the virtual environment, each participant moved the tip of their index finger from the warp origin in front of them straight to the target at the back. Only the virtual hand, displaced from the actual hand position corresponding to the amount of movement, was visually presented.

ABSTRACT

To increase the flexibility of haptic feedback in virtual reality (VR), hand redirection (HR) has been proposed to shift the hand's virtual position from its actual position. To expand the range of HR applications, a method to broaden the detection threshold (DT), which is the maximum amount of shift that can be applied without the user noticing, is required. Multisensory integration studies have revealed that the reliability of senses affects the weight of integration. To expand the DTs of HR, we propose a method to increase visual dominance in the integration of vision and proprioception by introducing noise to the latter, thereby decreasing its reliability through weak Gaussian white noise electrical stimulation ($\sigma = 0.5$ mA). The results of a user study comprising 22 participants (11 women and 11 men) confirm that noisy electrical stimulation significantly expands the DTs of HR with the mean range of DTs (R_{DT}) was 20.48° (SD = 7.90) with electrical stimulation and 19.15° (SD = 7.11) without electrical stimulation. Interestingly, this effect was only observed in women. The average R_{DT} for men was 15.36° (SD = 6.13) and 15.18° (SD = 5.58), whereas that for women was 25.61° (SD = 5.89) and 23.12° ($SD = 6.21$), with and without electrical stimulation, respectively. Electrical stimulation was mostly tolerable for the participants and did not affect embodiment or presence ratings. These results suggest that expansion of the DT without disturbing the user's VR experience is feasible.

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

1 INTRODUCTION

In virtual reality (VR), haptic feedback is essential in ensuring high immersion and operability. Passive haptics, wherein static objects are aligned with virtual objects for haptic presentation, has been proposed as an inexpensive and practical way to provide realistic haptic feedback [26]. When using passive haptics, visual dominance prevents the user from feeling uncomfortable even if there is a discrepancy between the position and posture of real and virtual objects. Futhermore, actively creating discrepancy improves the flexibility of the haptic feedback that can be presented with static objects [4, 30]. The technique of creating a discrepancy in position and/or posture between the real and virtual body without being noticed by the user is known as redirection. When applied specifically to the hands, this technique is called Hand Redirection (HR). As an example, Ban et al. [5–7] showed that if there is a discrepancy between the shape of a physical object being touched and that of its virtual counterpart, a spatial distortion can be obtained such that the shapes of the two coincide. A visual presentation of a virtual object and the displaced hand based on this distortion can give users a haptic shape perception of what they see within a certain range. Kohli et al. [30] proposed a similar method, redirected touching, which improves the flexibility of passive haptics by redirecting the hand position in VR. Azmandian et al. [4] improved upon these methods by developing a method called haptic retargeting that makes the correspondence between real and virtual objects flexible by discreetly manipulating the positions of virtual hands and orientation of the virtual environment.

If the discrepancy between the positions and postures of real and virtual hands exceeds a detection threshold, i.e., the maximal degree of manipulation that goes unnoticed by the user, discomfort will occur and the immersion will be disrupted. Zenner & Krüger [57] found this detection threshold to be 8.90° in the horizontal direction and 9.36° in the vertical direction. They also reported that the depth-wise detection threshold was +13.75% for the gain in the expansion (acceleration) direction and -6.18% for the gain in the contraction (deceleration) direction. This range constraint limits the flexibility of passive haptics and narrows the range of applications that can be exploited. Therefore, the realization of techniques that enable

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DOI 10.1109/ISMAR59233.2023.00119

greater discrepancy without being noticed by the user is an important challenge in the development of practical passive haptics.

Several studies have been conducted to expand the detection threshold for HR. Zenner & Krüger's study suggests that the detection threshold is expanded by distractor stimuli [57]. It has also been proposed to add discreet discontinuous displacements between blinks [58]. Focusing on the appearance of virtual hands, Ogawa et al. reported that more realistic avatars correlate with a lower likelihood for the user to notice redirection [40]. Hirao et al. reported that it is possible to obscure the discrepancy between the positions of real and virtual hands by applying noise to the proprioceptive perception using tendon vibration stimulation [23]. Recently, tendon vibration has also been shown to increase the emergence of a rubber hand illusion by serving as proprioceptive noise [9]. These methods can be interpreted as taking advantage of the fact that bodily perception follows multisensory integration models [11, 12, 31] to create conditions in which multisensory integration is more visually dominant. As an extension of this concept, we propose a novel method to expand the detection thresholds for HR by decreasing the reliability of proprioceptive signals. In this study, we focused on tendon electrical stimulation [28]. Whereas the constant electrical stimulation of tendons has been shown to alter the perception of body posture [50], few reports have examined the effects of white Gaussian noise as an electrical stimulus on perceived body position. In a related study, Matsumoto et al. [36] showed that noisy electrical stimulation to the vestibule can expand the detection threshold of redirected walking. Here, we hypothesized that the noisy electrical stimulation of tendons would reduce the reliability of proprioceptive signals and make the perceived body position in HR more visually dominant, and that this weak electrical stimulation would not disrupt the user's experience. Our results are significant not only because they may aid in the development of a more usable HR, but also because they reflect the potential of electrical stimulation as a new method to reduce the reliability of proprioceptive signals.

2 RELATED WORK

2.1 Hand Redirection

Passive haptics [26] is a strategy for haptic presentation in VR, where physical objects (haptic proxies) provide natural representations of virtual objects. To effectively use passive haptics, these proxies must (1) be co-located with the virtual objects and (2) have similar material and geometric properties with the virtual objects [34, 39]. Azmandian et al. [4] proposed a method called haptic retargeting, wherein colocation is realized by manipulating the virtual objects and environment. In haptic retargeting, a single physical object can represent haptic sensation for multiple virtual objects by adding a shift to the virtual hand's position or environment. The technique of shifting the virtual body's position or environment from its real counterpart is known as redirection. When the subject of manipulation is the hand, it is called hand redirection (HR). Several improved algorithms for HR have subsequently been proposed [10, 19] to shift the virtual hand's position so that the real hand touches the haptic proxy simultaneously, as the virtual object is visually touched by the virtual hand even if it is not in the same position as the haptic proxy.

HR is powerful for flexible use of passive haptics, but it also has certain limitations. If the shift between the real and virtual hands is sufficiently large to be noticed by the user, it inhibits the natural interaction or presence in VR. Recent studies have suggested that HR can also be applied to rehabilitation tasks to increase a sense of accomplishment or induce more significant physical movement in reality [20]. In this context, it is crucial to ensure that any spatial manipulation is unnoticeable. The maximum degree of unnoticeable manipulation, called the detection threshold, defines the scope of the application of HR. Zenner & Krüger [57] investigated specific detection thresholds by shifting the virtual hand via rotation around a specified pivot and acceleration/deceleration. Other studies have investigated the detection thresholds for HR using bimanual hands [18] and gain-based manipulation [13]. The detection thresholds are required to be expanded to realize the flexible use of HR.

2.2 Multisensory Integration

In HR, users are assumed to integrate vision (virtual hand) and proprioception (real hand) to estimate the hand position. Our study is based on the hypothesis that sensory integration in HR follows the maximum likelihood estimation (MLE) model [12]. When performing sensory estimation for multiple modalities, MLE assumes that the value of the highest likelihood calculated by multiple senses becomes the integrated sensory estimate. Information obtained from the senses with lower noise (variance) in the sensory signal, indicating higher reliability, is assigned more weight in the integration process. Conversely, signals with lower reliability are given less weight. For example, when sensory inputs from vision and proprioception (x_v, x_p) are integrated, the estimation y is as follows, where σ_v^2 and σ_p^2 represent instances of sensory noise.

$$y = \frac{\sigma_p^2}{\sigma_v^2 + \sigma_p^2} \cdot x_v + \frac{\sigma_v^2}{\sigma_v^2 + \sigma_p^2} \cdot x_p \tag{1}$$

In the context of multisensory integration, the Bayesian causal inference (BCI) model has also been proposed [11, 31]. BCI makes inferences by calculating posterior probabilities from the prior distribution and probabilities. It is a more complex model than MLE, mainly in that it considers the prior distribution. If that the variance of the prior distribution is assumed to be zero, the inferential process of BCI is similar to that of MLE [11]. In the present study, because body localization of the hand was reported to be explained by the MLE model with the visual and proprioceptive reliabilities [35], we adopted MLE as the basis of our hypothesis. In practice, however, factors considered in BCI, such as prior distribution, are expected to influence body localization.

2.3 Noisy Stimulation for Manipulating Sensory Integration

This study aims to increase the relative dominance of vision by introducing noise to proprioception to expand the detection thresholds for HR. Previous studies have shown that it is possible to increase visual dominance via noisy stimulation, specifically tendon vibration stimulation and galvanic vestibular stimulation [23, 25, 36]. Although these approaches were found to be effective, they present the limitations described below. These limitations are our motivation in proposing a new approach with noisy tendon electrical stimulation.

2.3.1 Tendon Vibration Stimulation

Vibrations externally applied to the proprioceptive receptors that receive position and force sensations can produce the illusion of motion and force [51]. Proprioceptive receptors include muscle spindles and Golgi tendon organs around muscles, tendons, and joints. Motion illusion occurs in the direction in which the stimulated muscle is extended. However, it is difficult to control the strength and direction of the illusion precisely. Hirao et al. [23] introduced tendon vibration stimulation as proprioceptive noise to extend the effect of pseudo-haptics, which affects force perception by visually presenting a body motion that is displaced from reality. They showed that tendon vibration stimulation makes it more difficult to perceive shifts in virtual body position. However, it was pointed out that the strong vibration required to stimulate the proprioceptive receptors is noticeable and inhibits the user's experience [28]. To obtain the full effect of tendon vibration, it was recommended to press the vibrating object firmly to the user's body [51], which would also undermine the user's comfort. In addition, vibration stimulation generates sound, which may further interfere with the VR experience or immersion.

2.3.2 Galvanic Vestibular Stimulation (GVS)

When the vestibule, a sensory organ in the inner ear that senses acceleration and balance, is stimulated with direct current, it produces a sensation of tilting toward the positive pole when electrodes are attached to both ears. This technique is called galvanic vestibular stimulation (GVS) [16, 17], and used to simulate a sense of equilibrium and acceleration in VR. [1, 2]. Matsumoto et al. [36] reported that white noise applied to the vestibule by GVS (noisy GVS) makes it difficult to notice changes in trajectory during redirected walking (RDW), a technique wherein the walking trajectory in VR is shifted to enable users to traverse in a large virtual space within a small real space [43]. A recent study has also shown that noisy GVS, bone-conduction vibration, and caloric vestibular stimulation expand the detection thresholds for RDW [25]. Other studies have investigated the effect of GVS on the perception of virtual hands. Some studies showed that left-anodal GVS increases the proprioceptive drift in the rubber hand illusion, which is a shift in the sense of position from the real hand to the rubber hand [41]. This indicates that GVS may be able to realize the visual-dominant integration of virtual hand's location, thereby expanding the detection thresholds of HR. In contrast, another study has shown left-anodal GVS to decrease the proprioceptive drift [15]. Thus, although GVS may affect the sensory estimation of the hand position, it is unknown whether it increases or decreases the importance of vision.

2.4 Tendon Electrical Stimulation

Transcutaneous electrical stimulation to proprioceptive receptors in tendons is known to generate motion illusion in a technique called tendon electrical stimulation. According to Kajimoto's study [28], AC stimulation to the arm produces the motion illusion of elbow flexion. Previous studies also induced motion sensation by stimulating the fingertips [55] and wrist [49]. Although cutaneous electrical stimulation stimulates cutaneous and proprioceptive receptors simulaneously, but the sense of motion is assumed to be caused by proprioceptive receptors [48]. It was also reported that the continuous electrical stimulation of tendons affects perceived body posture [50]. Recently, it was proposed to combine tendon electrical stimulation with haptic presentation to achieve realistic feedback for 3DUI manipulation [3]. However, the effects of noisy electrical stimulation of tendons on bodily perception have not yet been investigated.

3 PROPOSED METHOD: NOISY TENDON ELECTRICAL STIMULATION

We propose a novel method to expand the detection thresholds for HR by introducing noisy tendon electrical stimulation. We assume that body localization in relation to HR follows the MLE model and is integrated mainly from proprioception and vision. In MLE, the weight of each sense changes according to the reliability of senses. Moving the integrated hand localization closer to the visual information of the virtual hand is necessary to expand detection thresholds. According to the MLE model, two approaches may be adopted: increasing the reliability of visual information, or decreasing the reliability of proprioceptive information. Regarding the former approach, it has been reported that realistic avatars can expand the detection thresholds for HR [40]. Although it is possible to manipulate the reliability of vision by factors other than realism, there is a limit to the degree of manipulation of visual information. Accordingly, this study examines the approach to reduce the reliability of proprioception. This approach has been shown to decrease the perceptibility of hand displacement when using tendon vibration stimulation [23]. However, tendon vibration stimulation is a noticeable stimulus to the user, which may introduce problems by disturbing the VR experience. We therefore employed transcutaneous electrical stimulation, particularly tendon electrical stimulation, to add noise to proprioceptive receptors without undermining the VR experience. Unlike vibration stimulation, electric stimulation does not produce sound. Furthermore, tendon electrical stimulation is limited to the peripheral nerves, making it relatively non-invasive and safe compared to GVS. To the best of our knowledge, this is the first study to investigate the effect of noisy tendon electrical stimulation. We hypothesize that such stimulation functions as proprioceptive noise and leads to visual-dominant sensory integration, thereby expanding the detection thresholds of HR.

4 EXPERIMENT

A user study was conducted to test the effect of noisy tendon electrical stimulation on detection thresholds for HR. The experiment aimed to investigate whether electrical stimulation can promote a visually dominant perception to expand detection thresholds. HR detection thresholds were measured with and without electrical stimulation, and the results were compared in a within-participant design. Fig. 1 illustrates our experimental setup.

4.1 Hand Redirection Method

HR was applied following the method of Zenner & Krüger [57]. In this study, only a horizontal warp was used, which means that displacement between the real and virtual hands was constrained to the horizontal plane. To limit the number of experimental conditions and avoid imposing an excessive burden on the participants, the horizontal direction was assumed to be the commonly used direction in HR, as it was also the first manipulation direction used in haptic retargeting [4]. In a horizontal warp, the virtual hand was shifted right or left from its real position. Fig. 2 shows the top view of the HR manipulation applied in this study. The position vector of the virtual hand $\overrightarrow{p_v}$ is calculated by rotating that of the real hand $\overrightarrow{p_r}$ by a manipulation angle α with respect to the warp origin $\overrightarrow{o}$. If $\overrightarrow{f}, \overrightarrow{r}$ are orthogonal vectors spanning the horizontal plane and the vertical direction is $\overrightarrow{h}$, the following equations yield the real hand's height from the horizontal plane:

$$\begin{aligned} \overrightarrow{h} &= \overrightarrow{f} \times \overrightarrow{r} && (2) \\ height &= (\overrightarrow{p_r} - \overrightarrow{o}) \cdot \overrightarrow{h} && (3) \end{aligned}$$

Then the projection of $\overrightarrow{p_r}$ on the horizontal plane ($\overrightarrow{d_r}$) is

$$\overrightarrow{d_r} = (\overrightarrow{p_r} - height \cdot \overrightarrow{h}) - \overrightarrow{o} \qquad (4)$$

The projection of $\overrightarrow{p_v}$ on the horizontal plane ($\overrightarrow{d_v}$) is obtained by rotating $\overrightarrow{d_r}$ as follows.

$$\begin{aligned} \alpha_r &= \operatorname{atan2}(\overrightarrow{d_r} \cdot \overrightarrow{r}, \overrightarrow{d_r} \cdot \overrightarrow{f}) && (5) \\ \overrightarrow{d_v} &= \sin(\alpha_r + \alpha) \cdot |\overrightarrow{d_r}| \cdot \overrightarrow{r} + \cos(\alpha_r + \alpha) \cdot |\overrightarrow{d_r}| \cdot \overrightarrow{f} && (6) \end{aligned}$$

Finally, $\overrightarrow{p_v}$ is calculated by the following equation:

$$\overrightarrow{p_v} = \overrightarrow{o} + \overrightarrow{d_v} + height \cdot \overrightarrow{h} \qquad (7)$$

In short, the position of the virtual hand is obtained by rotating the position vector of the real hand (starting from the warp origin) by a certain angle (manipulation angle shown in the figure) in the horizontal plane. No manipulation was applied in the vertical direction, but only in the horizontal direction to rotate and shift the position of the virtual hand. Participants could move their hands upward or downward in the vertical direction from the horizontal plane where the warp origin and target object are located. Still, the height of the virtual hand was consistent with that of the real one.

Because only position is manipulated, the posture of the virtual hand corresponds with that of the real hand. In this study, the manipulation angle α is defined to be positive when the virtual hand is shifted to the right of the real hand. Similarly, negative α corresponds to leftward shifts.The position of the tip of the index finger is defined as the hand's position. To implement HR for experimental purposes, we employed HaRT (Virtual Reality Hand Redirection Toolkit) [56], a plug-in tool developed in Unity.

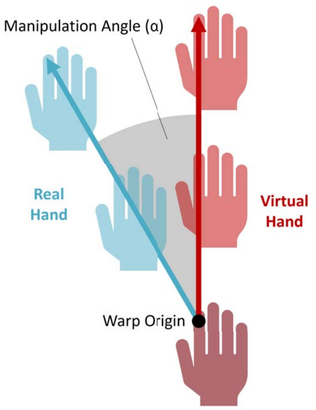

Figure 2: Top view of horizontal warp image [57]. The virtual hand is shifted rightward from the real hand.

4.2 1AFC yes/no question

The detection thresholds for HR were measured through a 1AFC yes/no question, wherein participants repeatedly experienced HR and responded if they noticed the displacement of hands. First, each participant moved the virtual hand from the warp origin to the target virtual object, while the virtual hand was shifted from the real hand. This task, called the reaching task, is illustrated on the right side of Fig. 1. All participants used their right hands for this task, regardless of their dominant hand, as a previous study has shown that hand dominance does not affect the detection threshold for HR [21]. They were instructed to maintain the pointing posture shown in Fig. 1 throughout the task. The warp origin (starting point of the task), represented by a spherical object, was 30 cm vertically down from the head-mounted display (HMD) attached to the participant's head and 30 cm in the frontal direction of the body. HR was applied after the hand (tip of the index finger) passed through the warp origin. The endpoint of reaching (target) was represented by a cube with its position 40 cm further from the start point in the frontal direction of the body. This setup follows that in Zenner & Krüger's study [57]. The warp origin and target were programmed to change from white to yellow when touched with the tip of the index finger of the virtual right hand. Note that a corresponding physical sphere or cube was not placed in the real space, meaning no haptic feedback was present.

In the 1AFC yes/no question, HR was repeatedly introduced while changing the manipulation angle. Participants were asked to specify whether they noticed the manipulation in each trial. A virtual whiteboard with a textual question and virtual objects for answering was presented following each reaching task with HR. The question was, "Did the movement of the virtual hand match the movement of the real hand? (Please answer with your left hand)." Participants then responded whether they perceived redirection in the previous reaching task by touching an object labeled "Yes" or "No" with their virtual left hand, which was synchronized with their real left hand. Because our system does not allow participants to modify their responses after answering, participants were instructed to verbally inform the experimenter if they needed to correct their answers in case of a mistake. We expected a greater degree of manipulation to correlate with a higher proportion of affirmative responses in regarding to noticing the manipulation. The distribution of this proportion was plotted against the degree of manipulation (manipulation angle) to fit a psychometric curve from which the detection threshold could be obtained. Such 1AFC yes/no question method have been conducted to measure the detection threshold for HR in previous studies [13, 18] alongside the pseudo-2AFC [57] and staircase [20, 40] methods. In our study, a total of 11 manipulation angles were used: ±15°, ±12°, ±9°, ±6°, ±3°, and 0°. For each condition with and without electrical stimulation, 10 trials were conducted for each of the 11 manipulation angles, for a total of 110 trials. Manipulation angles were presented in a randomized order for all 110 trials.

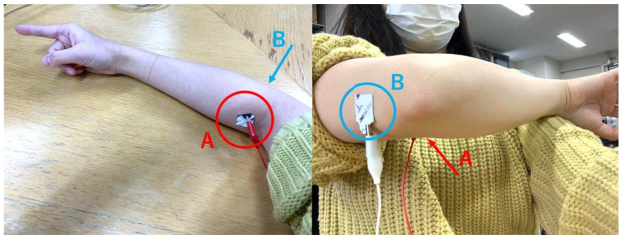

Figure 3: Electrode attachment positions. Electrodes A and B are intended to stimulate the tendons of the biceps and triceps brachii muscles, respectively.

4.3 Electrical Stimulation

Electrodes were attached at positions A and B as shown in Fig. 3. Because the biceps and triceps brachii muscles are respectively used for elbow flexion and extension, the simultaneous stimulation of these muscles' tendons by a noisy current is expected to introduce noise to the proprioception of the perceived hand position. Although electrical stimulation of the tendons and surrounding muscles may cause involuntary movements such as muscle contraction, it was assumed that such an effect does not occur when the white noise current does not exceed 1 mA. In this study, electrical stimulation was applied to the participant's right arm throughout the reaching task. The current waveform was white Gaussian noise, as in the study using noisy GVS for RDW [36]. The standard deviation of the current value was set to $\sigma = 0.5$ [mA], and its absolute value was limited to a maximum of 2σ (1 mA). The current value was set to a level that would not be unpleasant but perceivable. The absolute value was limited to prevent users from feeling pain or discomfort due to the instantaneous flow of high current.

4.4 Participants

Twenty three participants took part in the user study. However, one participant could not complete the task during the experiment due to difficulty concentrating as a result of lack of sleep. Thus, data from the remaining 22 participants (11 women and 11 men; age: M = 22.6, SD = 0.85) were included in the analysis. 21 of the 22 participants were right-handed, and one was left-handed. The number of participants was decided to be 22 to obtain sufficient statistical power (Power 0.8) for the effect of electrical stimulation based on the power analysis. After the experiment, participants received Amazon gift certificates worth 3,000 yen.Because the experiment used electrical stimulation, participants were required to not have any of the following conditions: allergic reaction to alcohol, mental or physical resistance to electrical stimulation, having a pacemaker or other devices affected by electric or magnetic fields, pregnancy, heart disease, neurological disease, brain disease, respiratory failure, visual impairment, and upper limb dysfunction.

4.5 Materials

To implement noisy tendon electrical stimulation, a dedicated electrical stimulator device was used. The device can output a specified current value regardless of the resistance value of its connected electrode. The waveform and current value specified by the computer are transmitted to the electrical stimulator device, which outputs the current via two electrodes.

Meta Quest 2 was used as the HMD to present the virtual environment, with a resolution of 1832 × 1920 for each eye and a refresh rate of up to 90 Hz. The hand tracking system, a function of Meta Quest 2, does not use the Touch controller, instead directly tracking the user's hand movements with the camera. This allows the virtual hands to mimic the position and posture of the real hands. The computer used for control was equipped with an Intel Core i7-8750H CPU@2.20GHz processor and NVIDIA GeForce RTX 2080 with a Max-Q Design graphics card. Windows 10 was used as the operating system. The virtual environment was developed in Unity 2019.4.33f1. The virtual hands were implemented as the white hands shown in Fig. 1. Furthermore, we used a plug-in called Oculus Integration to link with Meta Quest 2, and realized control of the electrical stimulator via serial communication from Unity.

4.6 Questionnaire and Interview

Questionnaires were used to obtain subjective indicators in the experiment. To examine effects on the sense of embodiment, immersion, and discomfort following 110 trials with and without electrical stimulation, participants answered the Virtual Embodiment Questionnaire (VEQ) [45], Igroup Presence Questionnaire (IPQ) [47], and three additional questions, awareness of electrical stimulation, discomfort with electrical stimulation, and naturalness of hand movements, using a Likert scale (1-7). All three indices of VEQ (ownership, control, and change) and four indices of IPQ (G1, SP, INV, and REAL) were analyzed. We used the Japanese version of each questionnaire. After completing 1AFC yes/no question measurements with and without electrical stimulation, we also conducted a verbal interview in Japanese, where the following questions were asked:

- How did you perceive the electrical stimulation; did you find it unpleasant?
- Can you tolerate such electrical stimulation when enjoying VR content?
- Did you notice any differences between conditions with and without electrical stimulation apart from the perception of electrical stimulation itself?
- Any other comments or impressions

It has been reported that the perception of the virtual body has some relationship with personality traits that have been linked to embodiment in previous studies. This is expected because the strength of the influence of prior knowledge in the BCI model exhibits a relationship with personality traits. Among several such traits, we focused on self-concept clarity (SCC) [8] and locus of control (LoC) [46]. SCC indicates the extent to which beliefs about the self are clearly and confidently defined, internally consistent, and stable over time. It has been reported that users with low SCC are more likely to experience a body ownership illusion [32]. In contrast, LoC is a measure of whether one attributes the consequences of their actions to internal factors, i.e., themselves, or external factors. Prior studies have shown that users with higher scores on the internal dimension of LoC are more likely to feel a sense of agency over the avatar's actions [27]. From these results, we examined the relationship between the detection threshold of HR and the personality traits. Before the 1AFC yes/no question task, participants were asked to answer a series of questionnaires to measure their SCC and LoC. To measure SCC, we asked for responses to 12 items on a five-point scale, yielding SCC index values in a range of 12-60, where higher scores indicate higher clarity of self-concept. For LoC, we measured scores on the internality dimension, associated with an individual's belief that their actions and decisions, rather than external events, have a significant impact on their life. To measure LoC, we asked for responses to 18 items on a four-point scale, yielding LoC index values in the range of 18-72, where higher scores indicate higher internality. We used the Japanese versions of both questionnaires [29, 52].

4.7 Procedure

The experiment was conducted according to the following procedure.

1. The participant was given a brief explanation of the experiment and provided consent to participate.
2. The participant answered the questionnaires regarding their personality traits.
3. Electrodes were attached to two locations near the participant's elbow, and connected to the electrical stimulator after wiping the skin at the electrode attachment points with a wet wipe.
4. After being given a description of the 1AFC yes/no question, the participant experienced the experimental environment and practiced the task several times. The practice session concluded when the participant was confirmed to understand the perception of redirection and how to complete the 1AFC yes/no question.
5. Detection thresholds were measured using the 1AFC yes/no question for each condition with and without electrical stimulation. The set of 110 trials for each condition lasted approximately 10 minutes. The electrodes remained attached to the participant under both conditions. After each condition, the participant responded to a questionnaire. The order of conditions (with and without electrical stimulation) was randomized among all participants.
6. After both sets of trials were completed, the participant was interviewed verbally about their experience throughout the experiment.

The whole process took approximately one hour, with variability among participants. Participants were allowed to take a break at any time. The experiment was conducted following the protocol approved by the Ethics Review Committee of the Graduate School of Information Science and Technology, the University of Tokyo.

4.8 Hypotheses

We expected the detection thresholds of HR to expand as a consequence of noisy electrical stimulation, which introduces proprioceptive noise to realize the visually dominant perception of the hand. Therefore, the first hypothesis was formulated as follows:

H1: Detection thresholds will be higher under electrical stimulation conditions than without electrical stimulation.

In addition, the weak electrical stimulation used in this study was expected not to interfere with the user's experience. Therefore, the second hypothesis was formulated as follows:

H2: Noisy electrical stimulation does not reduce the quality of the virtual experience.

We investigated SCC and LoC because both may be correlated with detection thresholds. Because the effects of personality traits that relate to self- and bodily awareness on detection thresholds are unknown, we examined the results in an exploratory manner without formulating any specific hypotheses.

5 RESULTS

In the following statistical tests, the significance level was set to $\alpha = 0.05$ unless otherwise specified.

5.1 Detection Thresholds

For each participant, psychometric functions were fitted for rightward and leftward shifts with and without electrical stimulation; thus, four psychometric functions were obtained for each participant. The proportion of affirmative responses in regard to noticing manipulation was plotted for each manipulation angle and fitted with a sigmoid curve. The analysis used a manipulation angle corresponding to a 50% response rate in the psychometric function as the detection threshold. Fig. 4 shows an example of a fitted graph of the psychometric function. Detection thresholds with four values,

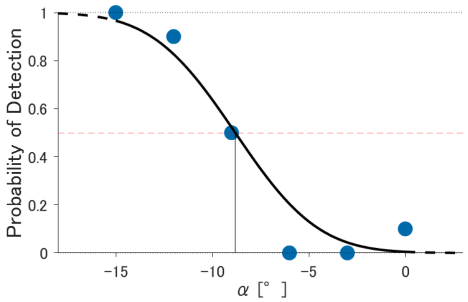

Figure 4: Sample graph of psychometric function fitted for leftward ($\alpha < 0$) manipulation.

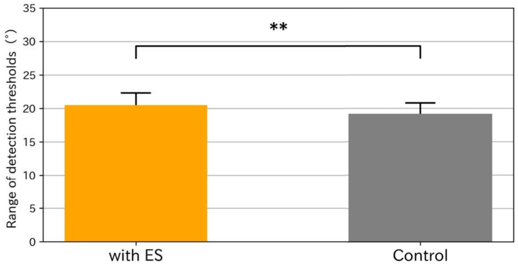

Figure 5: Bar graph of R_{DT} with and without (control) electrical stimulation (ES) conditions. The error bars indicate SEs. **: $p < .01$

rightward/leftward threshold × with/without electrical stimulation, were obtained for all participants. The difference between the left and right thresholds in each condition was taken to obtain the range of detection thresholds ($R_{DT} = DT_r - DT_l$).

Fig. 5 compares R_{DT} with and without electrical stimulation. After confirming the normality of these values with the Shapiro-Wilk test, a paired t-test confirmed that R_{DT} was significantly larger in the condition with electrical stimulation (M= 20.48°, SD = 7.90) than in the control condition (M= 19.15°, SD = 7.11) ($p = 0.0037$, Cohen's $d = 0.18$). Electrical stimulation increased R_{DT} by an average of 6.72% (SD = 10.61), with a maximal increase of 29.29%.

Fig. 6 presents a comparison of R_{DT} with respect to gender. The average R_{DT} for men was 15.36° (SD = 6.13) and 15.18° (SD = 5.58), whereas that for women was 25.61° (SD = 5.89) and 23.12° ($SD = 6.21$), with and without electrical stimulation, respectively. After confirming normality by the Shapiro-Wilk test, homogeneity of variance by the Levene test, and sphericity by the Mauchly test, a two-way ANOVA was conducted considering the within-participants factors of electrical stimulation and the between-participants factor of gender. The results indicate that both gender ($F(1,20) = 11.83, p = 0.0026, \eta_p^2 = 0.37$) and the presence of electrical stimulation ($F(1,20) = 16.37, p = 0.0006, \eta_p^2 = 0.45$) had significant main effects. A significant interaction effect ($F(1,20) = 12.36, p = 0.0022, \eta_p^2 = 0.38$) was also found. We subsequently conducted posthoc tests using the Bonferroni method (The significance level $\alpha = 0.0125$). First, student t-tests were conducted on the difference in R_{DT} between men and women. The result indicates a significant differences both with ($p = 0.0011$, Cohen's $d = 1.71$) and without ($p = 0.0070$, Cohen's $d = 1.34$) electrical stimulation. Next, paired t-tests were conducted for the effects of electrical stimulation in each gender. No significant expansion of R_{DT} was observed in men ($p = 0.74$, Cohen's $d = 0.03$). Conversely, a significant increase in R_{DT} by electrical stimulation was observed in women ($p = 0.000099$, Cohen's $d = 0.41$). Electrical stimulation increased R_{DT} by an average of 1.06% for men and 12.37% for women.

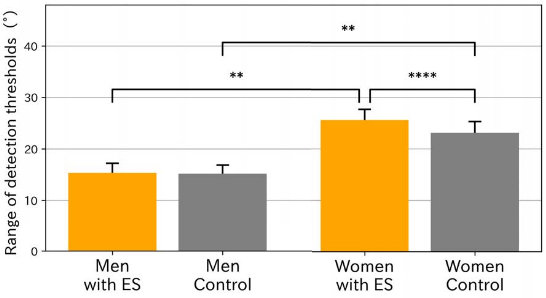

Figure 6: Bar plot of detection thresholds of men and women with and without (control) electrical stimulation (ES) conditions. The error bars indicate SEs. **: $p < .01$, ****: $p < .0001$

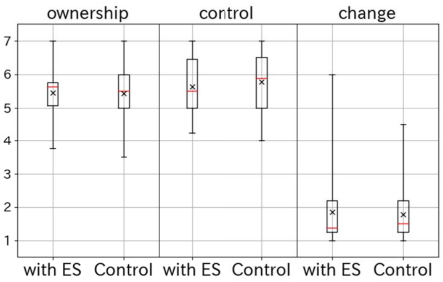

Figure 7: Box plot of VEQ scores with and without (control) electrical stimulation (ES) conditions.

5.2 Questionnaire and Interview

5.2.1 Sense of Embodiment and Presence

Fig. 7 shows the results of the VEQ. Values of three indices, ownership, control, and change, were obtained for each participant with and without electrical stimulation. The results of a Wilcoxon signed-rank test indicated no significant difference in any of the indices between the presence and absence of electrical stimulation (ownership: $p = 0.97$, Cohen's $d = 0.04$; control: $p = 0.22$, Cohen's $d = 0.17$; change: $p = 0.70$, Cohen's $d = 0.07$). The average responses to the question of "naturalness of hand movement" were 2.95 (SD = 1.64) with electric stimulation and 2.36 (SD = 1.46) without electric stimulation. In this context, a higher score indicates that hand movement was perceived to be more natural. A Wilcoxon signed-rank test showed no significant difference in responses to this question between conditions with and without electrical stimulation ($p = 0.12$, Cohen's $d = 0.38$).

Fig. 8 presents the results of the IPQ questionnaire. Values of four indices (G1, SP, REAL, and INV) were obtained for each participant with and without electrical stimulation. The results of a Wilcoxon signed-rank test revealed no significant difference in any of the indices between the presence and absence of electrical stimulation (G1: $p = 0.10$, Cohen's $d = 0.34$; SP: $p = 0.52$, Cohen's $d = 0.13$; REAL: $p = 0.97$, Cohen's $d = 0.01$; INV: $p = 0.85$, Cohen's $d = 0.15$).

5.2.2 Perception of Electrical Stimulation

In the condition with electrical stimulation, the average response to the question of "awareness of electric stimulation" was 3.64 (SD = 1.72), and that to the question of "discomfort with electric stimulation" was 2.55 (SD = 1.37). A higher score indicates a

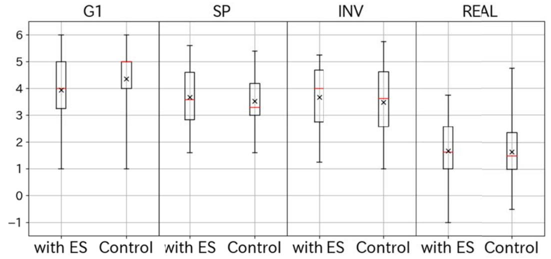

Figure 8: Box plot of IPQ scores with and without (control) electrical stimulation (ES) conditions.

greater degree of awareness or discomfort with electrical stimulation. No significant correlations were found between the scores of "awareness of electric stimulation" and the change in R_{DT} by adding electrical stimulation (correlation coefficient $r = 0.09, p = 0.70$), and the scores of "discomfort with electric stimulation" and the change in R_{DT} by adding electrical stimulation (correlation coefficient $r = 0.02, p = 0.93$). The average response to the question of "awareness of electric stimulation" were 4.27 (SD = 1.29) in women and 3.00 (SD = 1.86) in men, whereas those to the question of "discomfort with electric stimulation" were 3.09 (SD = 1.31) in women and 2.00 (SD = 1.21) in men. After confirming that the Bartlett's test did not violate the homogeneity of variance assumption, the results of a Wilcoxon rank sum test showed that there was no significant gender difference but a large effect size in the scores of "awareness of electric stimulation" ($p = 0.12$, Cohen's $d = 0.80$). There was a significant gender difference in the scores of "discomfort with electric stimulation" ($p = 0.041$, Cohen's $d = 0.87$).

Of the 22 participants, three male participants did not perceive any electrical stimulation. Of the remaining 19 participants who perceived electrical stimulation when not moving their hands, three answered that they had difficulty perceiving the electrical stimuli during the reaching movement. Furthermore, a variety of subjective sensations of electrical stimulation were reported, such as "an itchy feeling" and "similar to a numb sensation in my legs." When asked if the electrical stimulation used in the experiment was acceptable in VR content, most participants responded in the affirmative. However, four participants said that it may be unacceptable depending on how it is used, and three reported that the cord of the electrical stimulator interfered with their movement. Interestingly, one participant answered that the VR experience would be better with electrical stimulation than without because he thought it would enrich VR content. With respect to differences among conditions with and without electrical stimulation, three participants reported that "electrical stimulation obscures the presence and position of the actual hand," three others responded that "it was more difficult to control the hand with electrical stimulation," one claimed that "the sense of ownership of the virtual hand decreased with electrical stimulation," and one reported that "the sense of immersion in the virtual environment was higher with electrical stimulation." The other 14 participants reported no differences between conditions excluding the perception of the electrical stimulation itself.

5.2.3 Personality Traits

The mean value of the SCC was 40.91 (SD= 7.71). A correlation with ownership score in VEQ was not found either with ($r = 0.36$, $p = 0.10$) or without ($r = -0.003$, $p = 0.99$) electrical stimulation. Likewise, no significant correlation with R_{DT} was found either with ($r = 0.27$, $p = 0.23$) or without ($r = 0.17$, $p = 0.44$) electrical stimulation. The mean value of internality in LoC was 46.86 (SD= 6.17). A correlation with the control score in VEQ was not found either with ($r = -0.006$, $p = 0.98$) or without ($r = 0.018$, $p = 0.94$) electrical stimulation. However, a marginally significant correlation with R_{DT} was observed with electrical stimulation ($r = 0.42, p = 0.051$). No such correlation was found without electrical stimulation ($r = 0.36$, $p = 0.10$).

Furthermore, there were a significant positive correlation between SCC and the amount of change in R_{DT} due to electrical stimulation ($r = 0.48$, $p = 0.025$). In addition, a marginally significant correlation between internality and the amount of change in R_{DT} due to electrical stimulation was found ($r = 0.41$, $p = 0.055$).

6 DISCUSSION

6.1 Effect of Electrical Stimulation

The user study results indicate that noisy electrical stimulation to the tendons around the elbow joint increases R_{DT} for HR, which supports H1. It is assumed that electrical stimulation functioned as noise to the proprioception, and thus, the perception was integrated in a visually dominant manner as expected. These results correspond with those obtained in prior studies, as noisy stimulation to the vestibular expanded the detection thresholds of RDW [25,36]; however, our results were the first to obtain the detection thresholds of HR with tendon electrical stimulation.

There was a gender difference in the effect of electrical stimulation on the expansion of detection thresholds. Specifically, no effect was observed in men, whereas a significant effect was observed in women. First, it is possible that the same noisy stimuli may have had different effects because women and men have different sensory integration characteristics. Specifically, detection thresholds were larger in women than in men regardless of the presence or absence of electrical stimulation. This result is significant because there have been few reports on gender differences in baseline susceptibility to redirection in hand redirection. This may be consistent with prior studies examining detection thresholds for RDW [37,38] and rotational gains [54], which reported a wider range of detection thresholds in women compared to men. This suggests that men and women may differ in the predominance of each sense during sensory integration. Furthermore, it is possible that the distribution of current density differs owing to the gender differences in body size. Because women tend to have thinner arm than men, current density at the tendons was expected to be higher, which may lead to a greater effect of noisy stimuli. Alternatively, it could be attributed to the influence of varying subcutaneous tissue distribution and skeletal structure between men and women. Women generally exhibit a wider range of motion at the elbow joint and possess a higher amount of subcutaneous fat. It is possible that such individual and gender differences in biological structures may affect the effectiveness of tendon electrical stimulation.

Individual differences were observed in the perception of electrical stimulation, with some participants being unable to perceive it. Specifically, women perceived electrical stimuli more sensitively. Concerning sensitivity to electric stimulation, both the perception and annoyance thresholds were reported to be lower in women [42,44]. This gender difference can be explained by body size [33], which may affect the distribution of current density.In addition, it has been reported that the intensity of sensory reception may differ depending on the gender density of myelinated nerves. [24] In contrast, no correlation was found between the degree of perception of electrical stimuli and the increase of R_{DT}. This suggests that the threshold expansion effect can be generated even at an intensity where electrical stimulation is not perceived. The absence of correlation between the effect and the perception level of electrical stimulation is contradictory if we only consider physical differences, such as body size, as the cause of gender differences of the two. Accordingly, further investigation must consider individual sensory characteristics alongside the physical characteristics as a factor to affect the effect of the electrical stimulation.

There were no differences in any of the VEQ or IPQ indices, or the ”naturalness of hand movements” scores, between the presence and absence of electrical stimulation. In other words, electrical stimulation did not affect the sense of embodiment or presence, which supports H2. In terms of tolerance level, many participants found the electrical stimulation to be ”not unpleasant” and ”acceptable,” which further supports H2. Conversely, some participants reported that electrical stimulation made it challenging to control their hands or lowered their sense of ownership, so there may be a possibility that the electrical stimulation disrupts the VR experience.

6.2 Personality Traits and sensory integration

This study investigated the relationship between detection threshold of HR and personality traits related to embodiment. The results showed no correlation between SCC and the ownership score in VEQ (both with and without electrical stimulation).Krol et al. [32] suggested that low-SCC individuals were more susceptible to body ownership illusion. Their study used rubber hand illusion and body-swap illusion, both based on visual-tactile synchronization. In contrast, our study used a hand tracking system where the virtual hand synchronized with the real hand, although displacement was introduced by HR. This visuomotor synchronization may have produced a strong sense of ownership independent of SCC. Thus, ownership scores obtained with VEQ were sticking to a high level, and a ceiling effect may be occurring. The results showed no correlation between internality in LoC and sense of agency (both with and without electrical stimulation), which is inconsistent with the previous study [27]. Both in the previous study and our study, a virtual hand with hand tracking was employed. However, in contrast to our study, the previous study conducted a task requiring the participants to move their fingertips, which is considered more complex than the simple task of reaching. It is reported that better performance leads to higher agency [53]. The easy task in our experimental setup may elicit a high sense of agency even for those with low internality, resulting in no correlation between LoC and sense of agency.

SCC did not corelate with R_{DT} independent of electrical stimulation, and internality in LoC was marginally positively correlated with R_{DT} only when electrical stimulation applied. These findings indicate that the attributes of multisensory integration, particularly the degree of significance assigned to vision and proprioception in this case, remain unaffected by one’s conceptualization of self. On the other hand, SCC was positively correlated with the change in R_{DT}, and internality was marginally positively correlated with the change in R_{DT}. These results suggest that people with clearer beliefs about self are more susceptible to the influence of electrical stimulation, leading to an expansion of their detection thresholds. One possible explanation is that individuals with higher SCC or internality tend to maintain a distinct body image by adjusting the importance of prior knowledge and sensory information in multisensory integration. When exposed to a noisy sensory signal (e.g., proprioception with electrical stimulation), the integrated body image becomes less clear. However, individuals with a clear self-concept or a strong belief in personal control may strive to maintain the overall reliability of their body image by flexibly reducing the reliability of sensory information that contains the noisy signal. Thus, it can be suggested that SCC and internality are rooted in the flexibility of body image in one’s brain.

6.3 Limitations and Future Work

The limitations of our study may represent potential future directions of research. First, the number of participants was decided to obtain sufficient statistical power for the effect of electrical stimulation, which suggests that the separate analysis of males and females to analysis unexpected gender differences reduced the power of statistical analysis. It is desirable to increase the number of participants to ensure generalizability of our results. More accurate verification would be possible by targeting a more diverse group of participants, including factors such as age and sensory characteristics. It is also important to note that the investigation of detection thresholds for HR was limited to horizontal redirection. It has been reported that the detection threshold varies depending on the direction of motion [22]. It is necessary to verify whether noisy electrical stimulation increases thresholds in the vertical and depth directions. In addition, the use of electrical stimulation is problematic, as it cannot be used by pregnant women or people with certain diseases. Furthermore, the possibility of inducing involuntary movements cannot be ruled out with respect to differences in individual physique, which may pose a danger to individuals. There is also the problem of the power cord interfering with exercise when the device is attached, as some participants reported it annoying. It is undeniable that arm fatigue and habituation due to repeated trials affected the ease of noticing redirections, although breaks could be taken at any time. Yet, it is unlikely that these effects influenced the results of the analysis because the order of presentation of both the conditions and the manipulation angles were all random within the conditions. Moreover, the current value and stimulated positions were fixed throughout this study. It may be possible to develop a more effective and generalizable method by adjusting the current value according to individual characteristics such as body size. Relevantly, individual differences in accuracy of proprioception and its relationship to VR experience have been reported, and it is expected that the possibility of remapping technology tailored to individuals will be investigated [14]. Likewise, it may be possible to increase the thresholds with minimal discomfort by tailoring the electrical stimulation to each individual. In this study, electrical stimulation was applied only to the elbow joint area; however, the effect may be improved by combining electrical stimulation to other body parts. Finally, vibratory stimulation of tendons has also been proposed as a method to add noise to proprioceptive perception [23]. Although electrical stimulation is less likely to disturb the VR experience than vibratory stimulation, it may be necessary to confirm this notion by comparing the two, or it may be beneficial to combine both methods. Our research is valuable because it can cost-effectively develop the current visually-centered VR experience into a modality-rich one by demonstrating the effectiveness of technologies that easily generate visual-dependent perception. This can be applied to various VR technologies in the future, such as pseudo-haptics and RDW other than hand redirection. In addition, hand redirection technique is expected to be utilized in rehabilitation [20], and it would also be fruitful to investigate if our results can be applied to improve the effectiveness of rehabilitation.

7 CONCLUSION

This study proposed a method with noisy tendon electrical stimulation to expand the detection threshold for hand redirection, a technique that shifts the virtual hand’s position in VR. The results of our experiment confirmed that white noise electrical stimulation to the elbow tendon is effective in expanding the detection thresholds. This indicates that noisy electrical stimulation increase the reliance on vision over proprioception when estimating the locations of hands.Furthermore, electrical stimulation may increase the thresholds without impairing the user experience. Conversely, the effect of the electrical stimulation varied with respect to gender, as it was only effective for women in our setup. Our findings open up the possibility of a new technique, not limited to hand redirection, to induce visual-dominant sensory integration by decreasing the reliability of proprioception through noisy tendon electrical stimulation.

ACKNOWLEDGMENTS

This work was partially supported by Grant-in-Aid for JST PRESTO Grant Number JPMJPR22S9, ACT-X Grant Number JPMJAX22AG, and Moonshot Research & Development Program (JPMJMS2013).

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