

# Asura hands: Own and control two left hands in immersive virtual reality environment

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**Abstract**—Body ownership, which is the feeling that one’s body part belongs to oneself, and agency, which is the sense of being able to control one’s own body part, can be felt towards fake body parts and those depicted by computer graphics. As part of an attempt to transfer self-body awareness to fake body segments, we investigated whether body ownership and agency are felt towards two visible left hands in an immersive virtual reality environment. One of the two hands shown through virtual reality goggles spatially matched the unseen actual hand. The other hand was fake and displayed at either the 10-cm lateral or medial side of the position of the actual hand. These two left hands moved synchronously with the actual left hand. Participants completed a behavioral test and questionnaire after adapting to the two left hands. In the behavioral test, participants accessed randomly emerging spheres using the seen hands as fast as possible. They used the fake hand to touch a sphere when it appeared near the fake hand 41% of the time when the fake hand was displayed at the medial position of the actual hand. The results of the questionnaire suggest that agency was experienced for the two visible left hands for this condition. By contrast, body ownership was felt mostly against the displayed hand that was spatially consistent with the actual hand. These findings indicate that although agency can be simultaneously felt for two seen left hands, body ownership is felt only for either of the two visible left hands.

## I. INTRODUCTION

Body augmentation is an attempt at extending human body functions by attaching additional mechanical or electronic body parts to humans [1], [2], [3], [4], [5], [6]. For example, researchers have investigated a robotic finger that can be additionally worn on a human hand and controlled to improve dexterous hand manipulation and understand the extension of embodiment [1], [2]. In virtual reality environments and in using computer-aided techniques, such body augmentation can be achieved using computer graphics with relative ease [7], [8], [9]. For example, Asai et al. projected an elongated human hand to provide an illusory feel to reach for an object placed far from a human [9]. Body augmentation is partially based on the transfer of body ownership to observable objects. This effect is known as the rubber hand illusion [10], [11], which also holds in virtual reality environments [12], [13], [14], [15], [16]. Realistic human limbs depicted by computer graphics through virtual reality goggles are perceived as parts of one’s body. For the body-ownership transfer to effectively occur, some conditions should be met, such as spatiotemporal congruency [17], [18] in which visible fake and unseen actual human bodies

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appear and move synchronously from spatial and temporal aspects.

To measure the intensity of the transfer of self-body awareness to visible fake body segments, the feelings of body ownership and agency are investigated. Body ownership is the feeling that a visible fake body part belongs to one’s body. The sense of agency is the feeling that a visible fake body part or tool can be controlled. These feelings are investigated by questionnaires and measurements of human behaviors. Researchers have long discussed the relationship between body ownership and agency [19], [20], [21]. In general, both types of feelings should be intense in immersive virtual environments.

This study investigates whether body ownership and agency are experienced towards two visible left hands that move synchronously with an unseen actual left hand. One of the seen left hands is consistent with the position of the actual hand, whereas the other hand is positioned slightly different from the actual hand. To the best of our knowledge, similar investigations have yet to be reported. Earlier studies on supernumerary fingers and limbs tended to focus on the control methods and functions of extended body parts for particular tasks [1], [5], [6], [22], [23]. Conversely, three research questions motivated this study. First, do humans feel body ownership for the two visible left hands simultaneously? Second, do humans feel agency over the two visible left hands simultaneously? Finally, what is the condition that effectively elicits body ownership and agency for the two visible left hands? For this question, we compared two conditions, for which a fake visible hand was located at the lateral or medial side of the position of the actual unseen hand. Regarding the position and posture of the visible fake hand, large inconsistencies with the actual hand deters an effective body ownership transfer [24], [25], and the location of the visible fake hand is an important factor. Answers to the research questions provide a further insight into body augmentation.

## II. METHODS

### A. Apparatus

An Oculus Quest2 (Oculus VR, LLC., CA) was used for the virtual reality goggles. It displays an image with a resolution of  $1832 \times 1920$  pixels per eye at 72 Hz. The left wrists and fingertips were tracked by the built-in cameras of the goggles. The virtual environment was implemented with Unity 2020.3.35.f1.



Fig. 1. Two left hands seen in the virtual environment. During the adaptation phase, these hands are shown, and one matched the actual hand in terms of its position and posture. Both hands moved in synchronously with the unseen actual left hand.

### B. Participants

Eleven university students, who were unaware of the study objectives, participated in the experiment. They provided written informed consent before the experiment.

### C. Stimuli: Multiple visible hands

As shown in Fig. 1, participants could see two left forearms and hands. One was displayed at the position where their actual unseen hand existed referring to the 18 feature points of the actual left hand. The other, i.e., the fake hand, was displayed at a displaced position. The fake hand was positioned displaced 10 cm from the medial or lateral side of the actual hand. The two visible hands moved in synchronization with the participants' actual hand.

### D. Experiment procedure

The participants sat on chairs in a space where they could fully move the left hand. They then conducted three tasks. First, a 1-min adaptation task was performed, in which participants become familiar with the visible left hands. Second, a reaching task was conducted, in which participants touched a sphere appearing at random positions, to investigate how the two left hands were used. Finally, subjective intensities of the body ownership and agency were asked. Each participant conducted these tasks for two conditions. In one condition, the fake hand was displayed at the lateral side of the position of the actual left hand. In the other condition, the fake hand was at the medial side. These conditions were randomly ordered.

In the adaptation task, one of the left computer-graphics arms was displayed at the same position as the participant's actual left hand, and the other was displayed displaced 10 cm inside or outside of the actual hand position. The two hands and fingers followed the motion of the participant's actual left hand and fingers. During the experiment, participants were instructed to place their right hand on their lap and maintain their face and body orientation, while refraining from touching with their left hand. In the adaptation phase, for 1 min, participants moved their left hand as if stroking

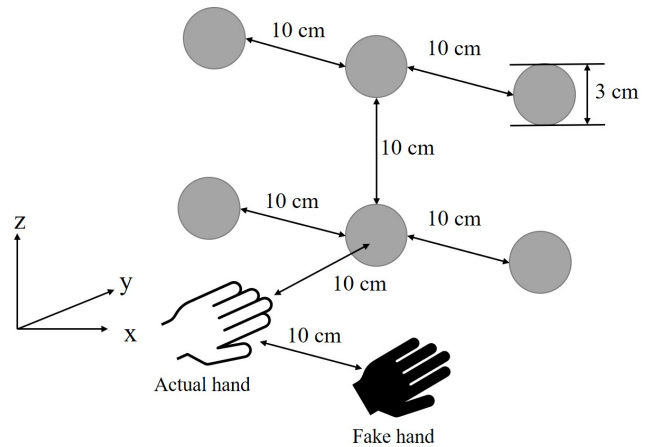


Fig. 2. Loci of spheres and actual and fake hands. The actual hand matched the participant's left hand in terms of its position and posture. Only one of the six spheres randomly appeared at any moment. Four of the six spheres were closer to the actual hand, and the others were closer to the fake hand. The figure shows the case in which the fake hand was displayed at the medial side of the actual hand.

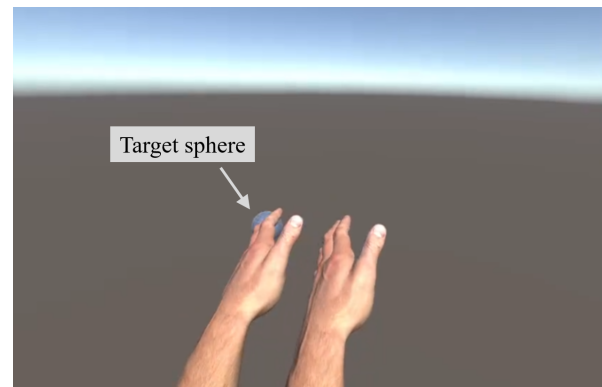


Fig. 3. Reaching task. The participants must touch the sphere that suddenly appears using their fingers as quickly as possible. The participants did not receive any instructions regarding which hand to use.

the surface of a sphere as large as the hand. The hand was in constant motion during this period. Participants were encouraged to stare at the two hands for an equally long period of time.

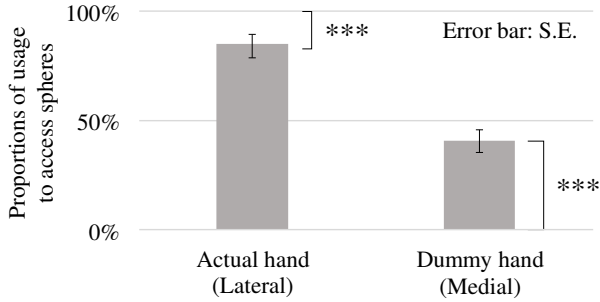
After the adaptation phase, participants performed a task of reaching for a sphere of 3 cm in diameter. As shown in Figs. 2 and 3, a sphere appeared randomly at one of six positions on the x-z plane set 10 cm in front the actual hand. Either of the six spheres was 10 cm from the neighboring spheres in the x and z directions. Four of the six positions were closer to the actual hand than to the fake hand. When the sphere was touched, it disappeared and the participant placed their left hand to the home position in front of the breast. A new sphere then appeared in a different location. The sphere's position referred to the actual left hand. Hence, the home position was not strictly controlled. This process was repeated 30 times with five replications for each sphere position.

After each experiment, the participants completed five

TABLE I  
QUESTIONNAIRE ITEMS

	Question	Category
Q1	I felt as if I owned two left hands.	Ownership
Q2	I felt as if the medial hand was mine.	Ownership
Q3	I felt as if the lateral hand was mine.	Ownership
Q4	I could control the medial hand.	Agency
Q5	I could control the lateral hand.	Agency
Q6	Which hand best matches the actual hand?	

(a) When the lateral hand matched the actual hand



(b) When the medial hand matched the actual hand

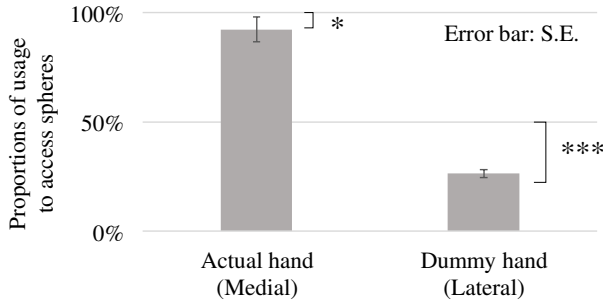


Fig. 4. Means and standard errors of the proportions of cases in which the hand closer to the sphere was used to touch it. (a) When the lateral hand matched the actual hand. (b) When the medial hand matched the actual hand. \* and \*\*\* indicate significant differences at  $p < 0.05$  and  $0.001$ , respectively.

questions on a 9-point Likert scale (1: disagree, 5: neutral, 9: strongly agree). Table I lists the questionnaire items. Three questions (Q1–Q3) concerned the sense of body ownership. Two questions (Q4 and Q5) concerned the sense of agency. Participants were also asked to indicate which hand, the medial or lateral hand, matched their actual left hand.

### III. RESULTS

Fig. 4 shows the means and standard errors of the proportions of cases in which the hand closer to the sphere was used to touch it.

Fig. 4 (a) shows the results when the lateral hand matched the actual hand. The lateral hand was used to touch spheres closer to the lateral hand at a proportion of  $0.85 \pm 0.04$  (the mean and standard error among the participants). If only the visible hand corresponding to the unseen actual hand was

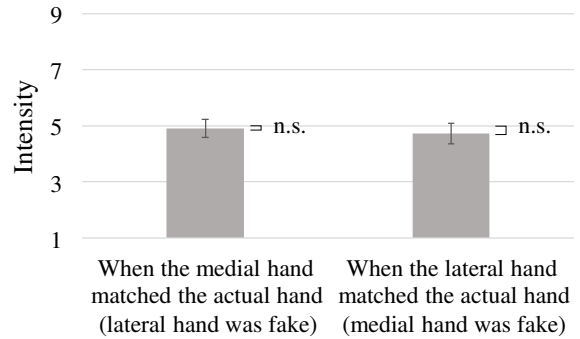


Fig. 5. Means and standard errors of the scores for Q1 (I felt as if I owned two left hands), which is a question regarding body ownership. (a) When the lateral hand matched the actual hand. (b) When the medial hand matched the actual hand. n.s. indicates not significant.

used, this proportion would be 1.0; however, 0.85 is significantly less than 1.0 ( $z = 6.23$ ,  $p = 4.66 \times 10^{-10}$ ). In some trials, participants reached for the sphere displayed near their actual hand using a relatively distant fake hand. Moreover, the mean proportion for the fake hand used to reach for the nearby sphere was  $0.41 \pm 0.06$ , which is significantly higher than 0 ( $z = 8.74$ ,  $p < 0.001$ ). Participants occasionally used the fake hand to touch the sphere when it was closer to the fake hand than to the actual hand.

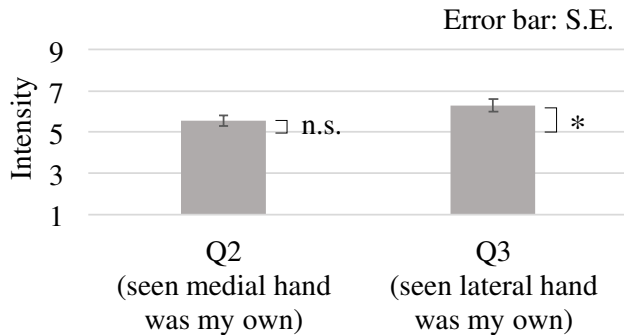
Fig. 4 (b) shows the results when the medial hand matched the actual hand. For this case, the actual hand at the medial side was mostly used to touch spheres at  $0.91 \pm 0.06$  when they were nearer to it. This value is slightly less than 1.0 ( $z = 2.33$ ,  $p = 0.020$ ). The fake hand at the lateral side was used at a proportion of  $0.25 \pm 0.03$  when the spheres were nearer to it. This proportion is greater than 0 ( $z = 4.28$ ,  $p = 18.7 \times 10^{-5}$ ). The fake lateral hand was also used to touch spheres at nearly a quarter of all the cases where the spheres were closer to the fake hand.

Figs. 5–7 show the results of the questionnaires. If the score was significantly above 5, body ownership or agency was considered to have been felt.

Fig. 5 shows the mean scores and standard errors for Q1 (I felt as if I owned two left hands). The scores were not significantly different from 5 irrespective of the position of the visible fake hand. This suggests that participants did not feel that they owned two left hands.

Fig. 6 shows the mean scores for Q2 (I felt as if the medial hand was mine) and Q3 (I felt as if the lateral hand was mine). Fig. 6 (a) shows the result for the condition when the lateral hand matched the actual hand. The mean score for Q2 was similar to 5 ( $t = -0.97$ ,  $p = 0.18$ ), whereas that for Q3 marginally exceeded 5 ( $t = -2.0$ ,  $p = 0.036$ ). These results suggest that ownership was felt for the visible lateral hand that was spatially congruent with the actual hand. Fig. 6 (b) shows the results for the condition when the medial hand matched the actual hand. The mean score for Q2 was significantly higher than 5 ( $t = -7.1$ ,  $p = 1.6 \times 10^{-5}$ ). The mean score for Q3 is significantly lower than 5 ( $t = 2.3$ ,  $p = 1.6 \times 10^{-5}$ ). Body ownership was felt for the medial

(a) When the lateral hand matched the actual hand



(b) When the medial hand matched the actual hand

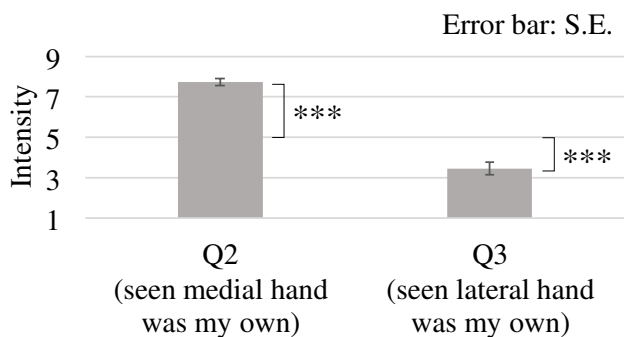


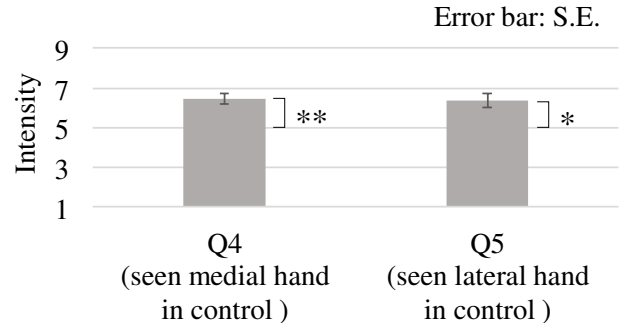
Fig. 6. Means and standard errors of the scores of Q2 and Q3. (a) When the lateral hand spatially matched the actual hand. (b) When the medial hand spatially matched the actual hand. \* and \*\*\* indicates a significant difference from 5 at  $p < 0.05$  and  $0.001$ , respectively. n.s. indicates not significant.

hand that matched the actual position, but not for the lateral fake hand. A significant difference is observed in the scores between Q2 and Q3 ( $t = 4.47$ ,  $p = 0.0012$ ). Participants felt that they owned the visible medial hand when it spatially matched the actual hand.

Fig. 7 shows the results for Q4 (I could control the medial hand) and Q5 (I could control the lateral hand). Fig. 7 (a) shows the mean scores for the condition where the lateral hand matched the actual hand. The mean scores for Q4 and Q5 were significantly higher than 5 (Q4:  $t = 2.6$ ,  $p = 9.2 \times 10^{-3}$ , Q5:  $t = -1.8$ ,  $p = 0.047$ ). Agency was felt for both visible hands, and the agency score was marginally greater than 5 for the lateral hand. Fig. 7 (b) shows the results for the condition when the medial hand matched the actual hand. The mean score for Q4 was significantly higher than 5 (Q4:  $t = -13.8$ ,  $p = 3.9 \times 10^{-5}$ ). Agency was felt for the medial hand when it matched the actual hand. However, the agency was not felt for the fake hand at the lateral side (Q5:  $t = 0.53$ ,  $p = 0.30$ ).

Q6 asked for which visible hand spatially matched the participant's actual hand. When the lateral hand matched the actual hand, 9 of the 11 participants selected the lateral hand. Two participants believed that the medial hand corresponded to their actual hand. When the medial hand matched the

(a) When the lateral hand matched the actual hand



(b) When the medial hand matched the actual hand

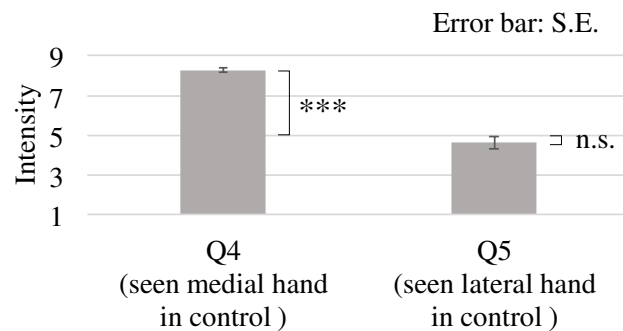


Fig. 7. Means and standard errors of the scores for Q4 (I could control the medial hand) and Q5 (I could control the lateral hand), which are questions regarding agency. (a) When the lateral hand matched the actual hand. (b) When the medial hand matched the actual hand. \*, \*\*, and \*\*\* indicates a significant difference from 5 at  $p < 0.05$ ,  $0.01$ , and  $0.001$ , respectively. n.s. indicates not significant.

actual hand, all the participants selected the medial hand.

#### IV. DISCUSSION

In this study, we examined whether body ownership and agency were experienced simultaneously for the two visible left hands. Our experiments showed that body ownership was not felt towards the two left seen hands simultaneously. In contrast, the agency was felt towards the two visible left hands when the additional hand was located at the medial side of the actual left hand. In this condition of the fake hand being shown at the medial side, two of the eleven participants believed that the medial seen hand matched their actual left hand. Furthermore, the medial fake hand was used to reach the target sphere for 41% of the time when a target sphere appeared near the fake hand. This proportion is significantly greater than 0%. These results collectively suggest that the two visible left hands were used as tools to reach for the random spheres by participants.

Hence, tentative answers to the three questions of this study are as follows. The first question was “do humans feel body ownership towards the two visible left hands simultaneously?” Our answer to this question is no. The second question was “do humans feel agency over the two visible left hands simultaneously?” Our answer to this question is yes.

The third question was “what is the condition that effectively elicits body ownership and agency for the two visible left hands?” Our answer to this question is that the additional hand should be placed at the medial side of the actual hand to increase the sense of agency.

We believe that the first research question remains inconclusive; that is, whether body ownership over supernumerary hands is experienced. Subsequent research must consider two major points before reaching a conclusion. First, the questionnaire may require revision. Q1 was “I felt as if I owned two left hands,” which disagrees with common sense; humans have only one left hand. Participants might have answered Q1 referring to their common sense rather than reflecting how they actually felt during the experiment. For example, Q1 could be revised to “sometimes I felt that I possessed the medial hand, and sometimes the lateral hand.” Second, the reaching task may require a redesign. In one condition, the sphere was placed 10 cm in front of the actual left hand position. In the other conditions, the sphere was placed 10 cm left or right from the position of the actual left hand. Hence, for two thirds of all cases, the spheres were closer to the actual left hand. Consequently, participants used the visible hand displayed at the position of the actual left hand more frequently than the fake hand. This design may have biased the senses of ownership and agency experienced by the participants.

Some aspects of our experimental design should be improved in the future. The introspective reports from the participants after the experiment indicated that participants were uncomfortable with the posture of the visible lateral hand when the fake hand was shown at the lateral side. In this experiment, the lateral fake hand was simply positioned 10 cm laterally from the actual hand. Naturally, its apparent direction should change accordingly.

## V. CONCLUSION

This study investigated the bodily self-consciousness towards two visible left hands in an immersive virtual reality environment; earlier studies mostly focused on how supernumerary hands or fingers can be controlled or leveraged for some tasks. As a result of the user study involving seven participants, body ownership was not simultaneously experienced for the two hands; however, only one of them was considered as the participant’s own limb. Most participants preferred the visible hand whose position matched that of the participants’ unseen actual left hand. However, in a task in which participants were required to quickly touch a sphere randomly appearing in front of them, both visible left hands were utilized. In the questionnaire survey, agency was experienced over the two visible left hands when the fake hand was at the medial side of the actual left hand. Hence, our study suggested that agency can be experienced for supernumerary hands with relative ease, unlike body ownership. Nonetheless, we intend to continue to pursue conditions for which body ownership transfers to supernumerary hands.

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