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Paper:

Changes in Body Representation of the Human Upper Limb as a Function of Movement and Visual Hand Position

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Several disease presentations are linked to a mismatch between the real body and the body's internal representation of itself. In order to develop effective rehabilitation therapies, it is necessary to understand the mechanisms underlying changes in body representation. In this study, we focused on changes in body representation of the upper limb as a large part of the body and investigated the conditions under which such changes occur. Participants were presented four conditions which differentially affected their sense of ownership and agency, including a movement condition related to their sense of agency, and a visual hand information condition related to the sense of ownership. In the experiment, participants were asked to move their upper limb forward and backward on a manipulandum. Results of the study showed that visual hand position affected changes in body representation relevant to both conscious and unconscious body parts. In addition, changes in the representation of the unconscious body part occurred with, and were dependent on, active movement.

Keywords: body awareness, body representation, proprioceptive drift, sense of ownership, sense of agency

1. Introduction

In recent years, the majority of developed countries are facing aging populations. Correspondingly, the incidence of movement disorders such as age-related locomotor disability, hemiplegia due to stroke and degenerative brain diseases are increasing. Movement disorders caused by brain diseases are a serious problem; experts believe that movement disorders may be related to a mismatch between the body and internal model of the body generated by the brain itself (known as a body representation). For example, the increase in falls as we age suggests that body representation has not adjusted to the loss of motor function we experience over time. In addition, hemiplegia may be explained by the idea that defective body representations are in conflict with normal motor functioning, and that this mismatch causes the disorder. In order to design more effective therapies, it is imperative to understand the relationship between the body and the brain's internal representation of the body.

Mirror therapy is a technique that has been shown to improve functioning in disease presentations resulting from a stroke such as hemiplegia [1–4]. Mirror therapy is a rehabilitation that uses a mirror to show patients their own healthy body parts [5]. For example, in mirror therapy, a patient may be shown the movement of their healthy hand in the mirror, causing them to feel as if the hand being they are viewing in the mirror was their diseased hand. This rehabilitative strategy is based on the idea of eliminating the mismatch that occurs between the body and the body representation of itself. The efficacy of mirror therapy can be explained by the fact that human perception is capable of producing changes in body representation; however, the mechanisms underlying these changes have not been fully elucidated. Although this form of rehabilitation has displayed therapeutic efficacy, so far, evidence-based guidelines for using mirror therapy have not been introduced. Because of this, understanding the mechanisms underlying changes in body representation are needed to develop more efficient and effective rehabilitative strategies.

The concept of a body representation is analogous to body image. A person's body image is grounded in their body schema, which is a collection of unconscious processes that allow the individual to register the position of their body parts, and are used in the spatial organization of movement [6]. A person's body image is the conscious representation of their own body [7, 8], and has a wide range of implications; however, for the purposes of this study, we focused on the location and locational relationship of the body parts because we consider that changes in body representation are mostly related primarily to the location of the body's various parts. Therefore, for the purpose of this paper, we define body representation as the location and locational relationship of the individual's perceived body parts.

Changes in the perceived location of body parts due to sensory input have been studied by many authors. In this study, we focused on the principle used in the rubber hand illusion (RHI), because this principle is analogous to rehabilitative techniques such as mirror therapy. RHI is a phenomenon in which the individual is made to feel as if the position of their hand changes from the actual hand to a fake hand with the application of a synchronous stimuli on an invisible real hand and visible fake hand [9–11]. In these studies, the proprioceptive position of the hand or finger perceived by the individual changes based on the effect of visual or tactile information and the movement, which known as proprioceptive drift. This proprioceptive drift can be explained by the fact that the body representation of itself changes following alterations in the visual and tactile information which it is receiving.

Studies suggest that synchrony in tactile information and visual resemblance between the real and fake hand is essential for the RHI phenomenon to occur. In addition, the sense of ownership and agency that individuals have are thought to be closely related to RHI [10, 12–15]. Sense of ownership and sense of agency are a part of subjective awareness for humans [16]. A person's sense of ownership refers to the feeling that "the object is my own," while a person's sense of agency refers to the feeling that "the agent who causes this action is me." In mirror therapy, it is assumed that patients feel a sense of ownership and agency over the image of the healthy hand portrayed in the mirror, and that this may explain why this therapy is effective for eliminating the mismatch between the body representation and the real body. This suggests that changes in body representation may be closely related to a person's sense of ownership and sense of agency. However, the studies described above were limited only to the hand. Studies are needed exploring the mechanisms involved in body representation in areas beyond the hand because movement disorders caused by brain diseases such as hemiplegia following stroke can affect vast areas of the body.

Recently, Ehrsson et al. extended the concept underlying the RHI phenomenon to the full body [17]. In this experiment, the authors let participants wear head-mounted displays and shot video of their backs. Videos were then shown to participants on a head-mounted display in real time so that participants could see their own back in front of them. Next, the authors stimulated participants' chest and the space under the video camera synchronously. The authors stated that participants reported feeling a sense of ownership over the image of the fake body displayed in front of them. In addition, the authors showed that the sense of ownership that the participants reported only occurred when the two stimuli were applied synchronously. Lenggenhager et al. conducted a similar experiment [18], and showed that participants reported feeling as if their bodies were moving away from them. Unlike the experiment by Ehrsson et al., Lenggenhager et al. measured the shift in the participant's perceived body location quantitatively. Moreover, participants reported that this artificial feeling as if their bodies were moving away from them was noticeable when the apparent body on the head-mounted display had a form similar to the human body.

Results of these experiments suggest that the body representation of large body parts can be altered using sensory input. However, these experiments described above used illusions of the whole-body location and investigated the location of the perceived body. It is questionable whether one can assume that the body representation of the whole body moved while maintaining its shape in these experiments. This point has been inadequately addressed by the previous studies.

Tsakiris et al. conducted an experiment similar to RHI investigating differences in proprioceptive drift related to the sense of agency and ownership under several conditions [15]. In this study, the authors stimulated the forefinger on the participant's real hand, as well as stimulating the finger on a fake hand, which in this experiment consisted of an image of the hand. The authors then investigated the proprioceptive drift that occurred in the forefinger and the little finger that was not stimulated. The authors found that participants displayed proprioceptive drift in the forefinger that was stimulated even when they only reported feeling a sense of ownership. On the contrary, proprioceptive drift occurred in both the stimulated forefinger and unstimulated little finger when participants moved their hand actively and reported feeling a sense of agency. Tsakiris et al. concluded that the sense of agency was responsible for the coherence in the body representation. Their research can be treated as an analysis of the relationship between changes in body representation and the sense of ownership and agency. The authors found that the body representation of the stimulated forefinger changed when participants reported feeling a sense of ownership or a sense of agency. Furthermore, the authors found that the body representation of the unstimulated little finger changed depending on the change in the body representation of the stimulated forefinger when the participants felt the sense of agency.

As previously explained, it has been shown that the body representation of the larger body part can move, but the events relative to the configuration of body representation remain unclear. Tsakiris et al. confirmed that changes in body representation differ among the different parts of the hand, and that this phenomenon depends on the conditions relative to the sense of ownership and sense of agency. Butz et al. conducted an RHI experiment using visualand tactile stimulation [19]. In this experiment, only the fake hand was presented to participants visually. The authors reported that the perceived angle of the elbow changed, although participants were not presented any visual presentation of the elbow. Based on these results, we anticipated that changes in body representation of the elbow would occur and that the changes would differ among the different parts of the upper limb. However, whether this will occur remains unclear. In this paper, we focused on the upper limb as a larger body part and performed an experiment similar to RHI. In this study, we analyzed changes in the body representation of the upper limb and measured the changes in the configuration of body representation. When analyzing the configuration of body representation of the upper limb, we treated the upper limb as a combination of two linked structures and measured the locations of the perceived elbow and finger.

The purpose of this paper was to investigate changes in body representation in the upper limb. Rather than solely investigating the location of the upper limb, we explored the changes in the configuration of the body representation by measuring the perceived finger and elbow locations.

During the study, we set up four experimental conditions based on activeness of movement and type of visual information. The four conditions were determined by the movement condition (active vs. passive) and visual hand position condition (congruent vs. incongruent). These factors were selected based on previous research [20]. These experimental conditions were chosen because these conditions have been shown to be strongly related to the sense of ownership and sense of agency. As explained above, sense of ownership and sense of agency are considered to be closely related to changes in body representation, and these will be discussed in this paper.

Based on previously published research, we propose the following hypotheses: First, the body representation of larger body parts can be changed. When such changes occur, they will differ according to part of the body. In the case of small body parts such as the hand, the pattern of changes is related to the individual's sense of agency or ownership. It possible that changes in the body representation associated with larger body parts will follow a similar pattern. In this study, we focused on conditions based on movement and visual hand position as the factors affecting sense of agency and ownership. We propose that such conditions will have an influence over changes in body representation for larger body parts.

2. Methods

2.1. Experimental Theory

In this experiment, we measured changes in the perceived location of the index finger and elbow in order to investigate changes in body representation in the upper limb. The experiment was designed to prompt changes in body representation under several experimental conditions. Participants were asked to make a simple movement, and altered visual information was presented to them during the movement. To measure changes in the perceived location of the body part being tested, we measured the position of the body part before and after upper limb movement.

In this experiment, we showed only the fake hand to the participants. Participants did not receive any other visual information during the experiment, and could not see their real upper limb nor the fake arm. This is based on the previously published research [19]. Butz et al. reported that the perceived angle of the elbow could be changed during experiments, even though participants were not presented any visual information about the elbow. Therefore, in this experiment, we decided not to display the fake elbow.

We set up four movement conditions relative to activeness and visual information.

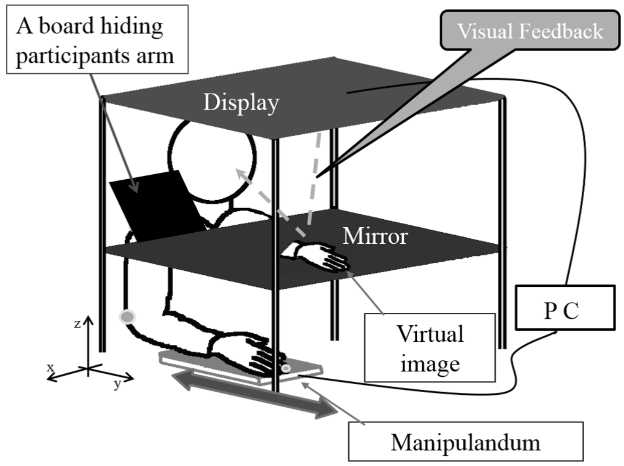


Fig. 1. Experimental device: Participants place their right hand on the manipulandum, and the hand is then tied to the manipulandum using a wrist band so that the wrist cannot move. The location of the manipulandum is observed and the location of visual feedback (virtual image of the hand and a part of the forearm) is controlled by a PC based on the location of manipulandum. The participants could not see their real arm, only the virtual image.

2.2. Experimental Apparatus

Participants were seated in a chair in front of a horizontal planar manipulandum (MP-201P, Uchida Electronics Co., Tokyo, Japan) fitted with two-joint mechanical arms to measure the positions of hand in the workspace.

Figure 1 shows the layout for the experimental device. **Fig. 2** shows the layout for the experimental device from a lateral view. The hand on the manipulandum was able to move freely on a 2D surface. Participants' right hands were secured to the manipulandum with a wristband so they could not move their wrist joint freely.

The only visual information participants were exposed to was a virtual mirror image, and participants could not see their actual arm. Only a virtual image of the right hand was shown. **Fig. 3** shows the virtual image used in the experiment. The virtual image depicted a hand and a part of the forearm. The size of the virtual image was adjusted so that it would be similar to the participant's actual hand.

The position of the manipulandum with the participants' real hand could be observed by researchers at all times, and the position of the virtual image was controlled by a PC based on the position of the participant's actual hand. The virtual image in the mirror was dis-

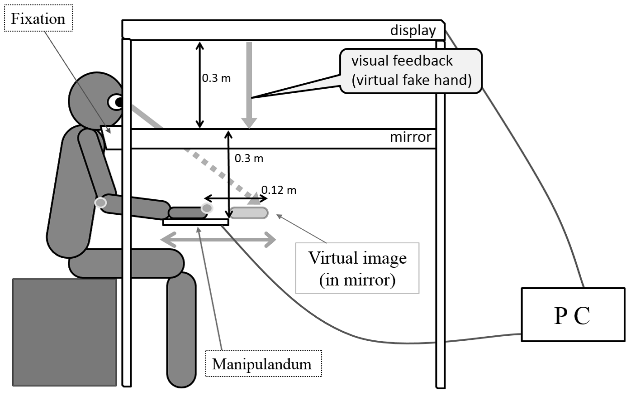
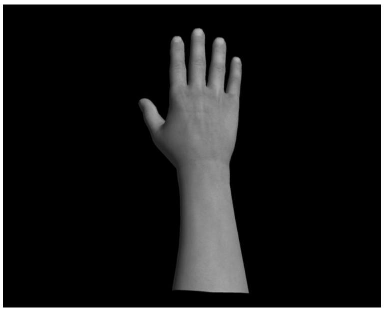
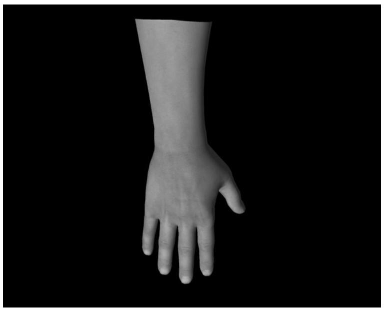


Fig. 2. Experimental device from a lateral view: The virtual image in the mirror was displayed 0.12 m ahead from the invisible real right hand throughout the experiment.



(a) Congruent position



(b) Incongruent position

Fig. 3. Virtual image: The virtual image included a hand and a part of the forearm. Under congruent conditions, the virtual image is shown in a correct position, while under incongruent conditions the image is shown in the opposite position.

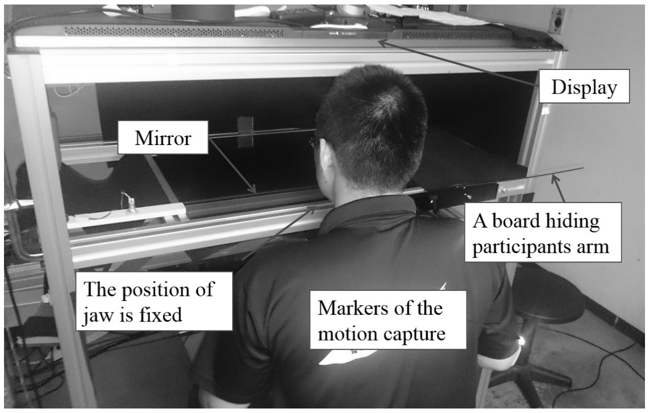


Fig. 4. Photograph of experimental device: As depicted in the photograph above, during the experiment, participants were seated in front of the experimental device, and the position of the jaw was fixed. A board was used to hide the participant's arm from view, and motion capture markers were placed on the participant's right elbow, and the tips of the right middle finger and the left index finger of the participants.

played 0.12 m ahead of the participant's invisible real right hand throughout the experiment. The appropriate distance between the participant's real hand and the virtual image was determined based on previously published research [21]. Kalckert and Ehrsson performed an experiment using the RHI. In this experiment, the authors compared sense of ownership, agency and proprioceptive drift between different condition on distance ; distance between real hand and rubber hand is 0.12 m and 0.275 m. They have reported that sense of ownership and agency at the 0.12 m distance are significantly higher than the 0.275 m distance. Also they have reported that proprioceptive drift is found at the 0.12 m distance rather than the 0.275 m distance. Based on these findings, 0.12 m was considered to be an appropriate distance for eliciting changes in body representation. When the hand on the manipulandum moved, the virtual image would produce the exact same movement under all conditions. The inherent time delay between the movement of the participant's actual hand and the movement of the corresponding virtual image was approximately 90 ms, so that participants could move the virtual image without the feeling of incompatibility.

Prior to starting the experiment, motion capture markers were placed on participants' right elbow, the tip of their right middle fingers, and the tip of the left index finger.

To provide visual feedback, a 46-inch monitor (LB-T461, SHARP, Osaka, Japan) supported by a custom-built aluminum frame was positioned at 0.6 m above the manipulandum with the screen facing down.

In order to maintain the duration of movements as constant as possible during the experiment, periodic pure tones (500 Hz in frequency and 100 ms in duration) were presented during the induction period. The delivery of visual images and experimental timing were controlled accurately using Presentation, Version 16.0 (Neurobehavioral Systems Inc., Berkeley, CA, USA). Presentation is a software application commonly used in psychological and neurobehavioral experiments that can create and deliver visual and auditory stimuli separately or simultaneously.

For the pointing judgment task (described below), we used a Flex 3 motion capture camera (OptiTrack, Ltd.). The sampling frequency for the Flex 3 was 100 Hz. An example of an actual photograph taken during the experiment is shown in **Fig. 4**.

Table 1. Questionnaire items: Questions 1 and 2 relate to the sense of ownership and Questions 3 and 4 to the sense of agency.

Question 1	I feel as though the virtual image is a part of the body
Question 2	I feel as though my hand is in the same position as the virtual image
Question 3	Virtual image moves in the direction chosen by me
Question 4	I feel that I control the movement of the virtual image

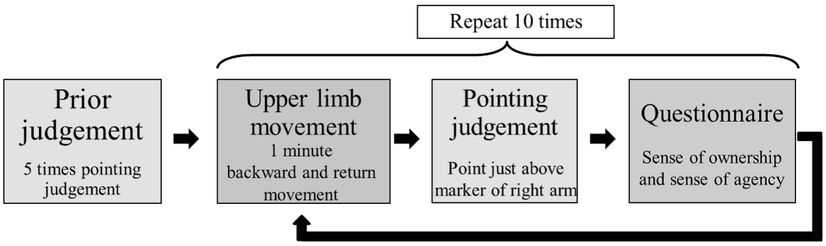


Fig. 5. Experimental flow.

2.3. Task and Condition

2.3.1. Task

To begin, participants were asked to position their right fingertip so that the virtual image would overlap with the starting point displayed in the mirror. Next, participants began to move their hand so that it would overlap with the goal point displayed in the mirror, which was positioned 0.06 m ahead from the starting point. Thereafter, participants returned their virtual image to the starting position. Using the steps described above, participants were asked to move their upper limb forward and backward, and this reciprocal motion was repeated every 3 seconds. The tempo of participant's movements was controlled using a sound played for participants and lasted for a total of 1 minute.

2.3.2. Experimental Condition

To test our hypotheses, we set up experimental conditions relative to the sense of ownership and sense of agency.

The experiment used a 2×2 factorial design: the conditions under which the participants felt both a sense of ownership and a sense of agency, where they felt only one of them, or neither. The first variable we used was the posture of the virtual image: congruent versus incongruent conditions. In the congruent condition, the virtual image was shown to participants in the correct position, while in the incongruent condition, the virtual image was reversed for participants. The second variable we used was movement: active versus passive movement. In the passive movement condition, movements of the arm were initiated by the experimenter. However, during passive movement, participants could not see the experimenter moving the manipulandum. Movement of the arm by the experimenter also followed the indicated sound and moved between the start and goal points identically to the arm movements initiated by participants under the active condition. These four factors were selected based on previously published research [20].

2.4. Evaluation of Sense of Ownership and Sense of Agency

Questionnaires were used to evaluate the participant's sense of ownership and agency. During the experiment, participants were asked to rate the sense of ownership and of agency they felt on a scale ranging from -3 (low agency/ownership) to $+3$ (high agency/ownership). Questionnaire items are shown in **Table 1**. Questions 1 and 2 addressed the participant's sense of ownership, while questions 3 and 4 addressed sense of agency.

Participants displaying higher scores on questions 1 and 2 were interpreted as having a stronger sense of ownership, and higher scores on questions 3 and 4 corresponded with a stronger sense of agency. Questionnaires such as these have been used commonly in previous studies to investigate participant's sense of ownership and sense of agency.

2.5. Pointing Judgment

To evaluate the human body representation, we measured the perceived position of the right fingertip and right elbow using a "pointing judgment" task.

During the task, participants were asked to point immediately above the location where they perceived their right elbow and the right fingertip marker using the left fingertip without any visual information. The placement of the left fingertip was recorded to identify the two-dimensional location of the participant's perceived elbow and finger using the motion capture system. During pointing judgement task, neither the virtual image of hand nor the elbow were shown.

2.6. Procedure

Figure 5 shows experimental flow for each condition. Prior to starting each task, participants received an explanation regarding the task and pointing judgment but were not given practice.

Before staring arm movements, participants were seated in front of the manipulandum and were asked to perform the pointing judgment tasks without visual information. During the task, participants were asked to point the perceived finger and elbow positions five times. This task was considered as the prior judgment.

After the prior judgment, participants were instructed to begin moving their right arm. After one minute, participants were asked to perform the pointing judgment task and answer questions regarding their sense of ownership and agency. This sequence of arm movement, pointing judgment task, and, questionnaire was repeated ten times for each condition to take into account dispersion of data.

Between conditions, participants were given a five-minute break. The length of the break was determined based on previously published research [22]. Asai et al. reported that at least a five-minute break was required before the proprioceptive drift was restored. Therefore, in this study, participants were given a five-minute break between conditions. The experiment lasted for approximately two hours per participant. The sequence of experimental conditions were not constant, and was varied depending on the participant.

2.7. Participants

A total of twelve healthy volunteers (7 male and 5 female; mean age 35.8 years, SD $= 10.7$) participated in the experiment. Prior to participation, all participants provided informed consent. All participants were right-handed, and the average score of Edinburgh Handedness Inventory was 90.8. Approval for the study was provided by the research ethics committee overseeing research at the University of Tokyo; the identification number is KE15-29.

3. Results

3.1. Questionnaire

Results of the questionnaire are shown in **Figs. 6** and **7**. Error bars depicted in each figure indicate the standard error of the mean (SEM) for each sample. Questionnaires are shown in **Table 1**. Sense of ownership scores were calculated as the average participant's scores for questions 1 and 2. In the same way, scores for sense of agency were calculated as the average participant's scores of questions 3 and 4.

Two-way repeated measures analysis of variance (RM-ANOVA) and generalized eta squared were used to estimate effect size [23, 24]. Results of the RM-ANOVA are shown in **Tables 2** and **3**. For the questionnaire items addressing sense of agency, only a main effect of movement condition was significant ($F(1,11) = 41.86, p < .01$). In addition, for items addressing sense of ownership, only the main effect of visual hand position condition was significant ($F(1,11) = 74.50, p < .01$). No significant interaction was detected in either questionnaire.

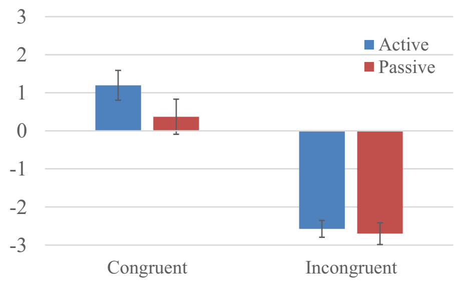


Fig. 6. Results of the questionnaire regarding the sense of ownership.

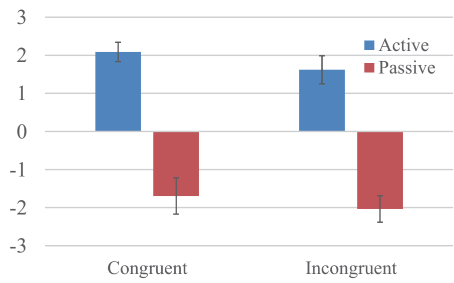


Fig. 7. Results of the questionnaire regarding the sense of agency.

Table 2. RM-ANOVA results of questionnaire (Sense of ownership): Condition A means visual hand position condition and B means movement condition ($*: p < .05, **: p < .01$).

	df	F-ratio	p-value	η_G^2
A	1	74.50	0.000 $**$	0.6818
B	1	3.75	0.079	0.0397
A×B	1	2.77	0.124	0.0219

Table 3. RM-ANOVA results of questionnaire (Sense of agency): Condition A means visual hand position condition and B means movement condition ($*: p < .05, **: p < .01$).

	df	F-ratio	p-value	η_G^2
A	1	4.34	0.061	0.0265
B	1	41.86	0.000 $**$	0.6965
A×B	1	0.23	0.639	0.0007

3.2. Body Representation Change

We evaluated changes in body representation by comparing the locations of finger and elbow perceived before and after movements. To analyze changes in body representation, we calculated changes in the perceived location of the finger/elbow on both the X-axis and Y-axis. X- and Y-axis are shown in **Fig. 1**. The point of origin on the x-y plane was the location of the starting point, as explained in Section 2.3.1. A movement towards the participant's

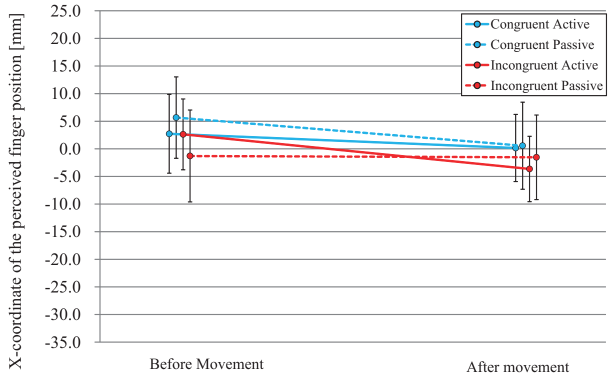


Fig. 8. X-coordinate of the perceived finger position.

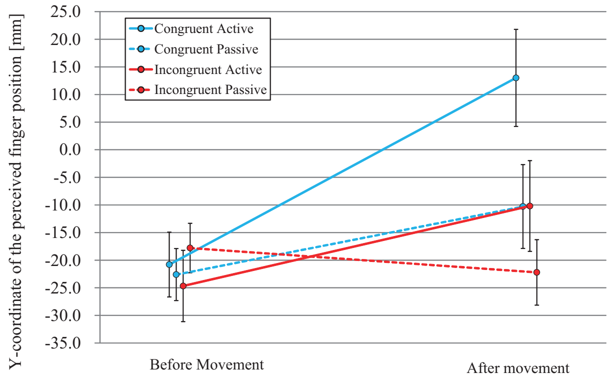


Fig. 9. Y-coordinate of the perceived finger position.

Table 4. RM-ANOVA results relevant to the movement of perceived finger location (x-coordinate): A means visual hand position condition, B means movement condition and C means before or after movement ($*: p < .05, **: p < .01$).

	df	F-ratio	p-value	η_G^2
A	1	1.03	0.333	0.0046
B	1	0.01	0.906	0.0001
C	1	1.47	0.250	0.0056
A×B	1	0.30	0.598	0.0007
A×C	1	0.04	0.840	0.0000
B×C	1	0.21	0.654	0.0003
A×B×C	1	2.53	0.140	0.0020

Table 5. RM-ANOVA results relevant to the movement of perceived finger location (y-coordinate): A means visual hand position condition, B means movement condition and C means before or after movement ($*: p < .05, **: p < .01$).

	df	F-ratio	p-value	η_G^2
A	1	6.97	0.023 ∗	0.0360
B	1	6.46	0.027 ∗	0.0284
C	1	7.45	0.020 ∗	0.0917
A×B	1	3.38	0.093	0.0126
A×C	1	9.74	0.010 ∗∗	0.0399
B×C	1	7.34	0.020 ∗	0.0495
A×B×C	1	0.11	0.747	0.0002

right side was considered a movement in the positive direction along the X-axis, while movement in the forward direction with respect to the participant was considered a movement in the positive direction on the Y-axis.

First, we describe the results relevant to the change in the body representation of the finger. In these experiments, we investigated changes in the perceived location of the finger before and after movement on the X- and Y-axis. Results are illustrated in **Figs. 8** and **9**. In the figures, error bars indicate the SEM for each sample.

Three-way RM-ANOVA was used to analyze results. Results of the RM-ANOVAs are presented in **Tables 4** and **5**. In the tables, Factor A refers to the visual hand position condition, Factor B to the movement condition, and Factor C to the timing of the pointing judgment.

Results show that, with respect to movement of the perceived finger location on the X-axis, there were no significant second-order interactions. Furthermore, no main effects and no significant interactions were observed.

With respect to movement of the perceived finger location on the Y-axis, results of the RM-ANOVA found no significant second-order interactions. However , the significant main effects were identified of all factors for which we tested. In addition, we identified significant interactions between Factors A (visual hand position condition) and C (the timing of pointing judgement) ($F(1,11) = 9.74, p < .01$), as well as Factors B and C (movement condition and the timing of pointing judgement) ($F(1,11) = 7.34, p < .05$). As a result of multiple comparison (Modified Sequentially Rejective Bonferroni Procedure), the effects of the Factors A ($F(1,11) = 11.41, p < .01$) and B ($F(1,11) = 8.55, p < .05$) were significant after movement and the effect of Factor C was significant under congruent ($F(1,11) = 12.39, p < .01$) and active conditions ($F(1,11) = 9.45, p < .05$). The interactions are shown in **Figs. 10** and **11**.

Next, we describe the results of our experiments investigating changes in body representation for the elbow. In these experiments, we investigated changes between the perceived location of the elbow before and after movement on the X- and Y-axis. Results of the experiments are shown in **Figs. 12** and **13**. In the figures, error bars indicate the SEM for each sample.

Three-way RM-ANOVA was used to analyze results for the elbow. Results of the RM-ANOVAs are presented in **Tables 6** and **7**.

In the direction of the X-axis, there was no significant second-order interaction. However, a significant interaction was observed between Factors B and C ($F(1,11) = 9.53, p < .05$). Result of multiple comparisons (Modified Sequentially Rejective Bonferroni Procedure), the effect of Factor C was significant under passive condition ($F(1,11) = 12.87, p < .01$). Interactions are shown in **Fig. 14**.

In the direction of the Y-axis, there was no significant second-order interaction. A significant interaction was observed between Factors B and C ($F(1,11) = 5.32, p <$

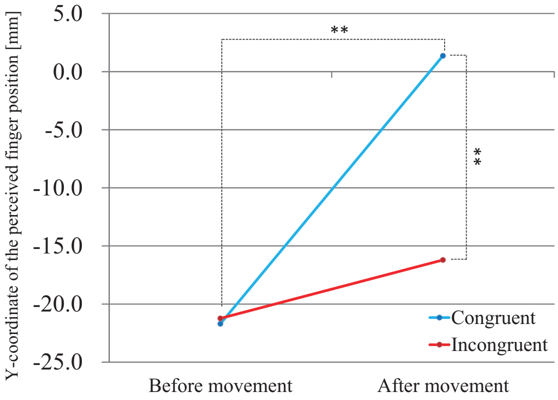


Fig. 10. Interaction between Factors A and C (finger, y-coordinate). $*: p < .05$, $**: p < .01$.

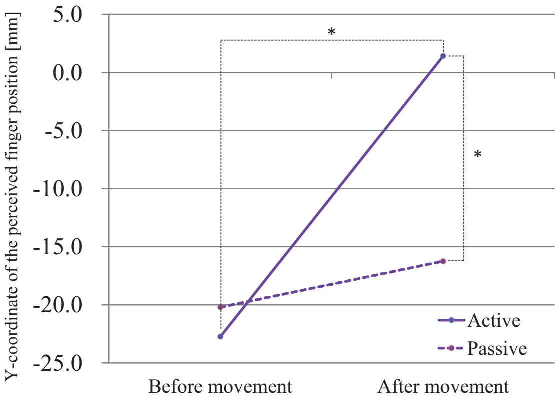


Fig. 11. Interaction between Factors B and C (finger, y-coordinate). $*: p < .05, **: p < .01$.

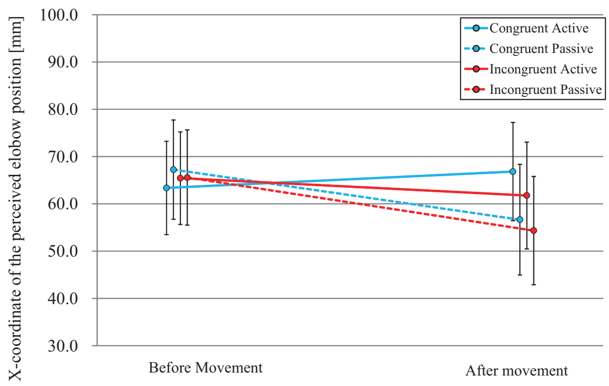


Fig. 12. X-coordinate of the perceived elbow position.

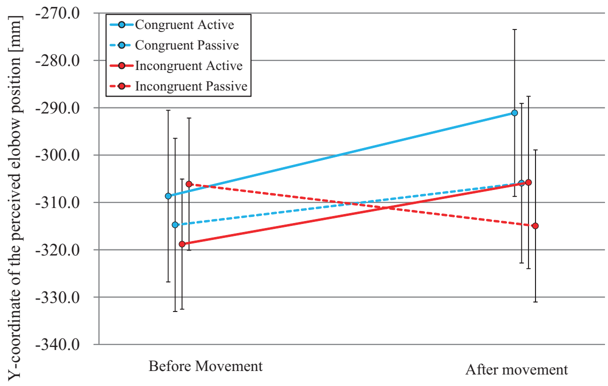


Fig. 13. Y-coordinate of the perceived elbow position.

.05). As a result of multiple comparison (Modified Sequentially Rejective Bonferroni Procedure), the effect of Factor B ($F(1,11) = 5.55, p < .05$) was significant after movement and the effect of Factor C was significant under active condition ($F(1,11) = 6.91, p < .05$). The interaction is shown in **Fig. 15**.

4. Discussion

First, we will assess the appropriateness of the conditions used in the experiments. In this study, we designed four conditions leading to the sense of agency and that of ownership, only one of them, and neither of the two. Results of the study found that participants reported feeling (1) both a sense of ownership and a sense of agency under congruent and active conditions, (2) feeling a sense of ownership only in the congruent + passive condition, (3) feeling only a sense of agency only in the incongruent + active condition, and (4) feeling neither a sense of agency nor ownership in the incongruent + passive conditions. In addition, results of the questionnaire found that experimental factors affected participant's sense of ownership and agency according to the experimental design. Thus, we can interpret that the position condition can control whether the participants feel the sense of ownership. Likewise, we can interpret that the movement condition determines whether the participants feel a sense of agency.

Next, we investigated changes in the body representation. First, we describe the results of the body representation change for the finger. Results of these experiments can be summarized by two phenomena. First, the perceived position of fingers did not change in the X-axis direction. Considering the fact that the virtual image was displayed 0.12 m ahead in the Y-axis direction, and that the movements we asked participants to perform were along the Y-axis, this outcome is not surprising. Second, results of our study also found that the perceived position of the finger drifted in a positive direction on the Y-axis under the congruent or active conditions. As described above, in this experiment, participants felt sense of ownership under congruent conditions, as well as feeling a sense of agency under active conditions. Graphs showing significant interactions related to this are shown in **Figs. 10** and **11**. This finding is consistent with previous research [9–15].

We then described the results of the body representation

Table 6. RM-ANOVA results relevant to the movement of perceived elbow location (x-coordinate): A means visual hand position condition, B means movement condition and C means before or after movement ($*: p < .05, **: p < .01$).

	df	F-ratio	p-value	η_G^2
A	1	0.34	0.570	0.0006
B	1	1.19	0.298	0.0023
C	1	4.06	0.069	0.0060
A×B	1	0.02	0.883	0.0000
A×C	1	1.19	0.299	0.0008
B×C	1	9.53	0.010 **	0.0058
A×B×C	1	2.06	0.179	0.0005

Table 7. RM-ANOVA results relevant to the movement of perceived elbow location (y-coordinate): A means visual hand position condition, B means movement condition and C means before or after movement ($*: p < .05, **: p < .01$).

	df	F-ratio	p-value	η_G^2
A	1	1.12	0.313	0.0032
B	1	1.38	0.265	0.0015
C	1	3.14	0.104	0.0047
A×B	1	3.65	0.083	0.0030
A×C	1	1.67	0.223	0.0025
B×C	1	5.32	0.042 *	0.0047
A×B×C	1	2.00	0.185	0.0009

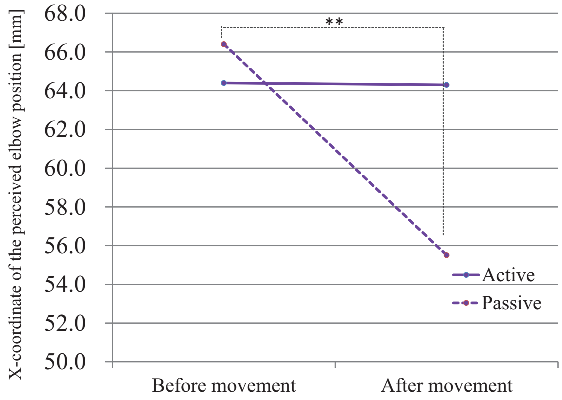


Fig. 14. Interaction between factors B and C (elbow, x-coordinate). $*: p < .05, **: p < .01$.

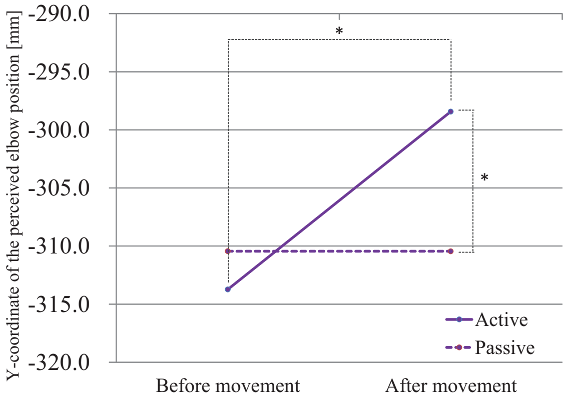


Fig. 15. Interaction between factors B and C (elbow, y-coordinate). $*: p < .05, **: p < .01$.

change for the elbow. In this study, the perceived position of the elbow drifted in a positive direction on Y-axis under active conditions (**Figs. 13** and **15**). As described above, in the active condition, participants reported feeling a sense of agency. In addition, when the virtual image was presented in congruent orientation, even when the perceived position of the finger drifted in a positive direction along the Y-axis, the perceived position of the elbow did not drift when the movement condition was passive. In the case of the active movement condition, the body representation of the elbow changed similarly to the body representation of the finger. This can be interpreted as meaning that the body representation of the elbow can change only when participants feel a sense of agency.

As explained by Ehrsson et al., the representation of large body parts can change, but the factors that are responsible for these changes in body representation are unclear. In this study, we found variations in body representation were different between large body parts (i.e., between finger and elbow). These variations were dependent on visual and movement conditions, considered as related to the sense of agency or that of ownership. This difference can be explained by the idea that the findings from previous research [15] were performed in larger body parts. Tsakiris et al. found that the amount of change that that participants felt in their body representation varied in different parts of the hand, and that the body representation change occurred across the whole hand when the participants actively moved their hand and felt the sense of agency. Tsakiris et al. postulated that the sense of agency was responsible for the coherence of the body representation. In this paper, we found that the same phenomenon occurs in different parts of the upper limb, which is larger than the hand. Our results show that the body representation of the whole upper limb can change under active condition. In addition, when body representation of the whole upper limb changed in our study, the representation of the elbow also changed accordingly.

The perceived position of elbow drifted in a negative direction on the X-axis under the passive condition (**Figs. 13** and **14**). Under passive condition, the participants did not feel the sense of agency. This can be explained by the idea that the perceived elbow approached the participants' body. In the absence of visual information, subjects tended to perceive their hand as being closer to their near side than it actually was [25]. From this, it is assumed that a similar phenomenon occurred with regard to participants' perceptions of the position of their elbow during movement in the absence of visual information confirming the location of elbow. However, the drift to X-axis negative direction was not observed when participants were asked to actively move their limb. Based on the second finding, both the body representation of the finger and the elbow can change under active condition. It is possible that as the body representation of upper limb expands, that the body representation of the elbow changes not only in the direction of the Y-axis, but also in the direction of the X-axis. However, the changes in the X-axis we observed were canceled by the phenomenon described above. Therefore, the perceived elbow did not drift in the X-axis with the sense of agency.

Finally, we summarize the main findings of this study. Under congruent or active conditions, changes in the body representation of the finger were altered by visual images. On the contrary, the body representation of the elbow changed only under active condition. This difference is thought to be due to the difference in the properties between the finger and elbow in this experiment. In this experiment, the finger was used as the representative point of the hand. The participants attempted to move the hand, and they received visual information in the form of virtual image. However, the movement of the elbow during this task was not actively controlled, that is, it was unconscious. Furthermore, during the task, participants received no visual information regarding their elbow. Therefore, we can conclude that the body representation of the whole upper limb changes under active condition, which is considered as the condition with a sense of agency. Under passive condition, the body representation of the finger changed under congruent condition, but the body representation of the whole upper limb does not. If the sense of agency is felt with active movement, the body representation of the whole upper limb and the elbow changed at the same time. Therefore, a sense of agency appears to be the necessary factor in changing body representation including changing the representation of body parts not under conscious control. When the sense of agency is felt under active conditions, the body representation of the unconscious body part can change depending on the change in the body representation of the other body part. We conclude that human body representation usually changes through the active body movement when the sense of agency is felt.

Several publications have addressed the use of virtual information in the rehabilitation of movement disorders induced by stroke or other degenerative diseases. Results of this paper suggest that the body representation of the elbow can change during movement of the upper limb with only a virtual image of hand when participants feel a sense of agency. Our hope is that this finding will lead to simpler, more effective rehabilitative strategies using virtual reality. Establishing the conditions that would allow for the most effective and efficient content or presentation of virtual information for patients will be crucial for optimizing rehabilitation therapies; modeling the changes that occur in body representation under different conditions may contribute to this process greatly.

Several limitations in this study need to be acknowledged. First, only two-dimensional measurements of the perceived position were collected in this study. Second, additional studies will be needed to investigate changes in body representation that occur over time during rehabilitation therapy. Finally, changes in body representation should be modeled mathematically in future studies.

5. Conclusion

In this study, we evaluated changes in body representation in the upper limb, considering the effect that different movement conditions (active vs. passive) and visual hand position condition (congruent vs. incongruent). The experiment was performed using four conditions, which lead participants to have different perceptions regarding the sense of ownership and the sense of agency. Analysis of our questionnaire showed that movement and visual hand position conditions are closely related to the sense of ownership and agency.

Results found that the body representation of the conscious body parts changed based on reception of a congruent visual image or performance of an active movement. In addition, results showed that the body representation of an unconscious body part changes under active conditions, and the activeness is the necessary factor for the change. These results suggest that the activeness of the human movement may be an important factor in the general body representation change.

Together, these results contribute to the growing understanding of the mechanisms underlying changes in body representation, and may help in the development of rehabilitation therapies for movement disorders caused by a mismatch between the real body and the body representation.

Acknowledgements

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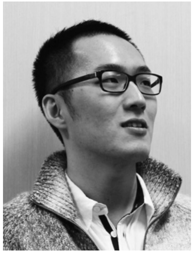

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