Robotically Enhanced Rubber Hand Illusion

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Robotically Enhanced Rubber Hand Illusion

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Abstract—The rubber hand illusion is a well-known multisensory illusion. In brief, watching a rubber hand being stroked by a paintbrush while one's own unseen hand is synchronously stroked causes the rubber hand to be attributed to one's own body and to "feel like it's my hand." The rubber hand illusion is thought to be triggered by the synchronized tactile stimulation of both the subject's hand and the fake hand. To extend the conventional rubber hand illusion, we introduce robotic technology in the form of a master-slave telemanipulator. The developed one degree-of-freedom master-slave system consists of an exoskeleton master equipped with an optical encoder that is worn on the subject's index finger and a motor-actuated index finger on the rubber hand, which allows the subject to perform unilateral telemanipulation. The moving rubber hand illusion has been studied by several researchers in the past with mechanically connected rigs between the subject's body and the fake limb. The robotic instruments let us investigate the moving rubber hand illusion with less constraints, thus behaving closer to the classic rubber hand illusion. In addition, the temporal delay between the body and the fake limb can be precisely manipulated. The experimental results revealed that the robotic instruments significantly enhance the rubber hand illusion. The time delay is significantly correlated with the effect of the multisensory illusion, and the effect significantly decreased at time delays over 100 ms. These findings can potentially contribute to the investigations of neural mechanisms in the field of neuroscience and of master-slave systems in the field of robotics.

Index Terms—Rubber Hand Illusion, Multisensory Illusion, Robotic Instruments, Master-Slave System

1 Introduction

When we look at or touch our hands, we immediately feel that they are part of our own body. Body ownership is the sense that one's body is one's own [1]. The rubber hand illusion (RHI) [2]–[10] is a well-known multisensory illusion involving body ownership. A commonly performed RHI configuration is shown in Fig. 1. The subject is seated with his/her right arm resting on a table. A standing screen is positioned beside the right arm to hide it from the subject's view, and a life-sized rubber model of a right hand is placed on the table directly in front of the subject. The subject's arm and the fake arm are covered from the subject's view. Then, tactile stimulation is given by stroking the subject's hidden hand and the rubber hand with a paintbrush, synchronizing the timing and position of the brushing as much as possible. After several tens of seconds of stimulation, the subject experiences an illusion in which he/she seems to feel the touch not of the hidden brush but of the viewed brush as if the rubber hand had become his/her hand [2]. Thus, RHI can be regarded as an illusion in which body ownership is transferred from the subject's hand to the fake hand due to tactile stimulation.

Recently, important insights regarding RHI have been reported by Makin [6] and Tsakiris [7]. The mechanisms of the multisensory illusion in RHI were recently investigated in the field of neuroscience using functional magnetic resonance imaging (fMRI) [8]–[10]. The body ownership transfer in RHI has been extended to a whole-body image as an "out-of-body experience" [11]–[14]. Although some advanced studies on different aspects of RHI exist, the neural mechanisms of RHI are not yet fully understood.

The proprioceptive drift (also called localization error, as illustrated in Fig. 2) has been widely introduced to evaluate the magnitude of the multisensory illusion in RHI (e.g., [2]–[5] and [9]). To measure the proprioceptive drift both before and after tactile stimulation, the subject is instructed to perform a series of intermanual reaches. With their eyes closed, the left index finger is drawn along a straight edge below the table until it is judged to be aligned with the index finger of the right hand, which rests on the table in the same position for all of the experiments (proprioceptive localization). The subjects' reaches after experiencing the illusion are displaced leftward toward the rubber hand; then, the magnitude of this drift varies significantly in proportion to the reported duration of the illusion [2]. This drift is the so-called proprioceptive drift. Therefore, the proprioceptive drift can be regarded as an evaluation index of how much the subject was influenced by RHI.

2 Purpose

In conventional RHI, the tactile stimulation is given by stroking the subject's hidden hand and the rubber hand with a paintbrush. Therefore, the tactile stimulation given to the subject in RHI is called passive touch since the subject's hand and the rubber hand are immovable. Active and passive touch have been distinguished since the early period of haptic research as follows: "Active touch refers to what is ordinarily called touching. This ought to be

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Fig. 1. RHI is a well-known multisensory illusion in which the subject feels the touch not of the hidden brush but of the viewed brush as if the rubber hand has become his/her hand.

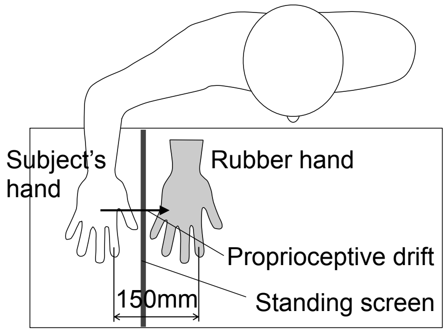

Fig. 2. The proprioceptive drift can be measured as the distance between the position of the subject's right index finger before and after the tactile stimulation, which is indicated by the subject's left hand below the table with his/her eyes blindfolded.

distinguished from passive touch, or being touched" [15]. In the present paper, we introduce robotic technology to investigate the effect of active touch in RHI.

We developed a one degree-of-freedom (DOF) master-slave system consisting of an exoskeleton master equipped with an optical encoder that is worn on the subject's index finger and a motor-actuated index finger on the rubber hand, which allows the subject to perform unilateral telemanipulation. Thus, the subject actively moves his/her index finger, and the robotically driven rubber hand's index finger performs the same motion simultaneously. As related research, Walsh et al. [16] reported that RHI can be induced by tapping movements of the index finger using a moving rubber hand that is mechanically connected to the subject's hand. The robotic instruments let us investigate the moving rubber hand illusion with less constraints, thus behaving closer to the classic rubber hand illusion. In addition, the temporal delay between the body and the fake limb can be precisely manipulated. We thus investigated the effect of active interaction in RHI between the body and the fake limb, which has not been widely explored in past studies since the experimental rigs have not been equipped with robotic instruments. Therefore, this paper presents an initial attempt to study the effect of multisensory illusion in RHI with robotic instruments.

3 METHOD

We developed a rubber hand master-slave system (RH-MSS) to investigate the effect of active interaction in RHI. We first designed a simple task to be performed using the system – a table-tapping task by the index finger – since the task includes the subject's voluntary motion and the haptic feedback resulting from hitting the table. In addition, the system must be compatible with the conventional RHI setup for comparison. Therefore, a 1 DOF index finger metacarpophalangeal (MCP) joint is implemented on both the master and slave in RH-MSS. The mechanical structure and characteristics of the developed system are described in this section.

3.1 Master

The master was implemented as an exoskeleton device that can be worn by the subject's right hand, as depicted in Fig. 3. The master is equipped with an optical encoder (MEH-9-1000PST16C, Microtech Laboratory Inc., Japan) with a resolution of 1000 pulses/rotation multiplied 16 times; thus, the resolution is 0.0225 deg. The encoder enables the measurement of the rotation angle of the MCP joint of the subject's index finger. The master is 110 mm in height, 90 mm in width, 50 mm in depth, and 79 g in mass. The dimensions were defined based on the Japanese anthropometric database [22]. The master was fabricated using ABS resin for a lightweight implementation and is equipped with mechanical hinges and sliders in four parts, making it adjustable for different subjects. The master can be fixed on the subject's right hand with Velcro straps on the index finger and the thumb as shown in Fig. 3. Note that the master is equipped only with an optical encoder and no actuators. In performing the table-tapping task, the subject can directly tap the table while wearing the master; thus, the actual reaction force and tactile sensation on his/her index finger can be obtained.

3.2 Slave

The slave was implemented as a 1 DOF robotic hand, as depicted in Fig. 4. The MCP joint of the index finger is actuated by a DC servo motor (2232A-024SR with gear head 22E and optical encoder IE2-512, Faulhaber GmbH, Germany). The motor is 75 mm in length and 22 mm in diameter; thus, it can be implemented in a life-sized human hand. The mechanical structure of the slave was fabricated using ABS resin for a lightweight implementation. The slave is 170 mm in height, 50 mm in width, 85 mm in depth, and 278 g in mass. The slave is approximately the size of a life-sized human hand; thus, it can be covered by the rubber hand, as shown in the right panel of Fig. 4. The slave was covered by the rubber hand in all of the experiments conducted in this paper. The index finger and the thumb were fabricated using soft urethane resin (Exseal

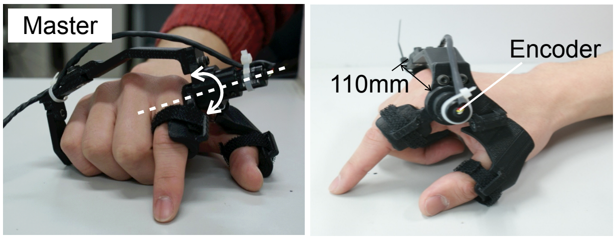

Fig. 3. The master was implemented as an exoskeleton device that can be worn on the subject's right hand. The master is equipped with an optical encoder that enables the measurement of the rotation angle of the MCP joint of the subject's index finger.

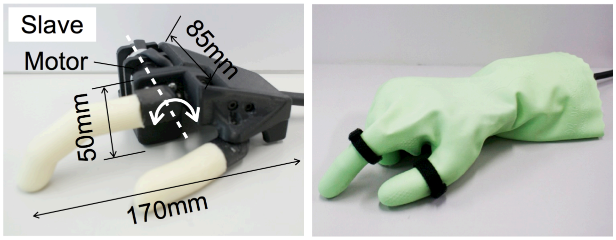

Fig. 4. The slave was implemented as a 1 DOF robotic hand using a DC servo motor. The size of the slave is approximately that of a life-sized human hand; thus, it can be covered by the same rubber hand used in the conventional RHI experiment.

Inc., Japan), which has a similar hardness as human skin. Therefore, the fingers naturally deform like human fingers during the table-tapping task to perform with human-hand-like behavior.

3.3 Control system

The control system of RH-MSS was developed using Matlab xPC target (The MathWorks, Inc., USA) with simple position control in a 1 kHz control loop. The control loop was designed using PID control, in which the PID parameters were manually tuned. The rotation angle of the subject's MCP joint at the index finger is measured by the optical encoder equipped on the master and is then fed back to the 1 DOF slave motion. Therefore, RH-MSS performs unilateral telemanipulation. Fig. 5 shows the results of the motion test performed to investigate the system performance by sending a position command similar to that of the table-tapping task (motion period of 2 s and stroke of 30 deg). The test showed that the system has a time delay of 2 ms due to the mechanical power transmission and electrical signal transmission, and the observed angle error was 0.017 deg (measured by peak-to-peak value of trajectories between the master and the slave). Since the error is undetectable by human subjects and the predicted time delay in this study was from 50 ms to 300 ms, we concluded that this system has sufficient performance to be used in this study.

3.4 Measurement

Active interaction such as a table-tapping task using the index finger can be performed by introducing the developed RH-MSS. The goal of the study is to determine how much the active motion influences the multisensory illusion in RHI. As conducted in previous studies ([2]–[5] and [9]), we used the proprioceptive drift as a psychophysical measure to investigate the effect of multisensory illusion. To measure the proprioceptive drift, the subject is blindfolded, and the subject's left index finger is guided to the right edge of the table by the experimenter. Then, the subject is asked to slowly slide his/her left index finger toward the left until the position where his/her right index finger

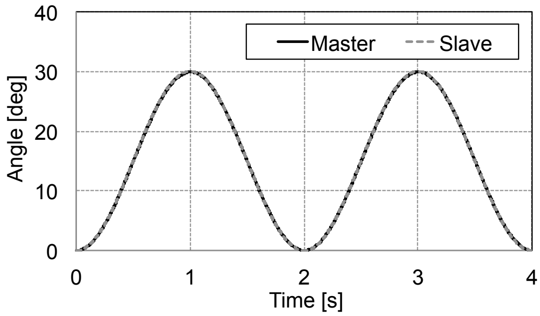

Fig. 5. The slave performed position control based on a given target position from the master. The system showed sufficient performance to be used in the experiments.

is supposed to be located on the table. We then measure the shift distance between the points where the subject manually pointed before and after the haptic stimulation using a scale. Thus, the measurement took place once before and once after the trial – a total of two times for each trial. Note that the subjects were only blindfolded during the measurements of proprioceptive drift. In addition, we conducted a questionnaire test based on a past study [2]. The questionnaire includes the five statements described in Table 1, including the predicted phenomena (Q1, Q2, and Q3: illusion statements) and the unpredicted phenomena (Q4 and Q5: control statements). Each subject was asked to answer the questionnaire with a score from 0 (lowest) to 5 (highest).

4 RESULTS

In this study, we conducted two experiments to investigate the effect of multisensory illusion using the developed robotic instruments.

4.1 Experiment on active touch

The aim of the active touch experiment is to investigate the effect of active touch in RHI using RH-MSS.

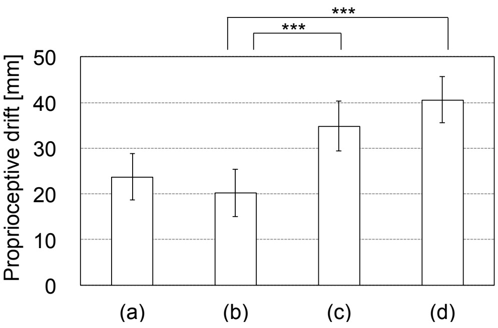

Fig. 6. The experiment was conducted under the following conditions: (a) conventional RHI, (b) conventional RHI with RH-MSS, (c) active touch with RH-MSS, and (d) active and passive touch with RH-MSS. A larger proprioceptive drift means a larger effect of the multisensory illusion. The proprioceptive drift showed a significant increase in (c) and (d) ($p<0.001$ ***, two-tailed paired samples t-test). The error bars indicate the standard error.

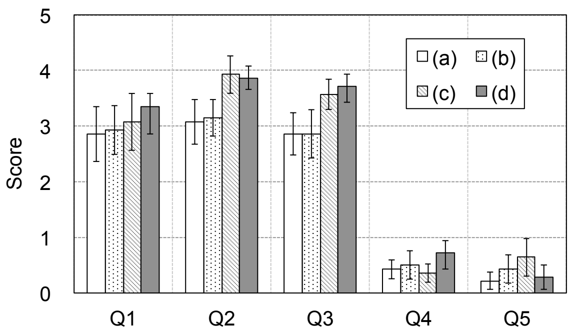

Fig. 7. The results of the questionnaire test show a similar tendency as that reported in the past RHI study. From the questions on the predicted phenomena (Q1, Q2, and Q3) that were configured to evaluate the strength of the multisensory illusion. From the questions on the unpredicted phenomena (Q4 and Q5), the scores were all low, thus showing the validity of the experiment. The bars and error bars indicate the mean value and standard error, respectively.

4.1.1 Experimental setup

Fourteen right-handed healthy subjects (including two females, aged 21–25 years) took part in the experiment. A standing screen was positioned beside the right arm to hide it from the subject's view. The rubber hand (in condition (a)) or the slave (in conditions (b), (c), and (d)) was placed on the table directly in front of the subject. The subject's right arm and the fake arm were also covered (see Fig. 1). The subjects were instructed to conduct four trials under the conditions described below in a random manner. After each trail, the subjects were instructed to answer the questionnaire test.

(a) Conventional RHI: Conventional RHI was conducted. First, the proprioceptive drift was measured before the trial. Then, five minutes of tactile stimulation were given by stroking both the subject's hidden hand and the rubber hand with a paintbrush with a period of approximately 1–3 s, synchronizing the timing and position of the brushing as much as possible. Then, the proprioceptive drift was measured. The subject was instructed to answer the questionnaire (Table 1) after the measurement of proprioceptive drift. Note that RH-MSS was not used in this condition.

(b) Conventional RHI with RH-MSS: Conventional RHI was performed using the RH-MSS setup. Although RH-MSS was used, motion was not performed by either the subject or the robot. This experiment was conducted under the same conditions described in (a) for the other conditions.

(c) Active touch with RH-MSS: Using RH-MSS, the subject was instructed to comfortably perform a table-tapping with a period of approximately 1–3 s for 5 minutes. No particular control of the rhythm was given to the subject. Then, the proprioceptive drift was measured. Note that brushstrokes were not given to the subject during the trial. This experiment was conducted under the same conditions described in (a) for the other conditions.

TABLE 1
Questionnaire including five statements: three predicted phenomena (Q1, Q2, and Q3) and two unpredicted phenomena (Q4 and Q5)

No.	Question
Q1	It seemed as if I were feeling the touch in the same location on the rubber hand.
Q2	It seemed as if the touch I felt was caused by the touch on the rubber hand.
Q3	I felt as if the rubber hand were my hand.
Q4	It seemed as if I might have more than one left hand or arm.
Q5	It appeared (visually) as if the rubber hand were drifting toward the left (toward my other hand).

(d) Active and passive touch with RH-MSS: The subject was instructed to perform a table-tapping task (just as in condition (c)) for 30 s. Then, 30 s of tactile stimulation was given by stroking the subject's hand and the slave with a paintbrush. This combination of haptic stimuli was repeated five times for a total of 5 minutes. Then, the proprioceptive drift was measured. This experiment was conducted under the same conditions described in (a) for the other conditions.

4.1.2 Experimental results

Fig. 6 shows the experimental results for the proprioceptive drift for each condition. A larger proprioceptive drift means a larger multisensory illusion effect. The result for condition (a) was similar to the result reported in past publications since the experimental setup was the same as that of conventional RHI studies. The proprioceptive drift for condition (b) was rated similar to that of condition (a) without significant difference. Condition (c) showed a significant increase in the proprioceptive drift over that of condition (b) ($p<.0001$, two-tailed paired samples t-test).

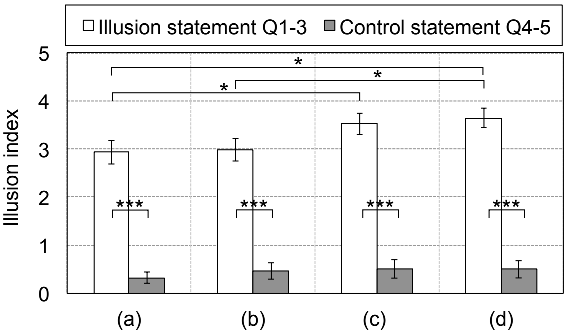

Fig. 8. The illusion index was computed by averaging the scores from the illusion statements (Q1–3) and the control statements (Q4–5) on each subject. Significant differences were observed in all cases (p<0.05 *, p<0.001 ***, two-tailed paired samples t-test). The error bars indicate the standard error.

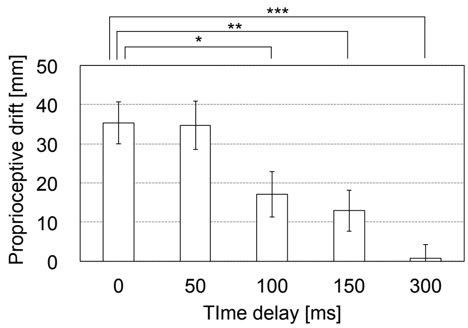

Fig. 9. The proprioceptive drift for each time delay condition is shown. The proprioceptive drift significantly decreased in the case where over 100 ms of time delay was configured (p<0.001 ***, p<0.01 **, p<0.05 *, two-tailed paired samples t-test). The error bars indicate the standard error.

This indicates that active touch is effective at inducing a multisensory illusion in RHI. The results clearly show that the effect of RHI can be robotically enhanced by introducing active touch. In addition, in condition (d), both active and passive haptic stimuli were given to the subject, and the proprioceptive drift significantly increased compared to (b) ($p<.0001$, two-tailed paired samples t-test). A significant difference was not observed between condition (c) and (d) ($p=0.2108$, two-tailed paired samples t-test).

Fig. 7 shows the results of the questionnaire tests conducted after each trial. The scores of the predicted phenomena (Q1, Q2, and Q3) were configured to evaluate the strength of the multisensory illusion. The results showed a similar tendency in the previous study [2]. From the questions on the unpredicted phenomena (Q4 and Q5), the scores were all low, which showed the validity of the experiment. Fig. 8 shows the computed illusion index for each condition, which can be given by averaging the score from the illusion statements (Q1–3) and control statements (Q4–5) of each subject. Significant differences were observed between the illusion and control statements in all cases. This statistically shows that the multisensory illusion could be elicited in all cases, including in the case where the robotic instruments have been utilized. In addition, significant differences were observed between illusion indexes (a) and (c), (a) and (d), and (b) and (d), which statistically show the illusion was stronger in these cases on a subjective level.

4.2 Experiment on time delay

The active interaction in RHI allowed by RH-MSS lets us also investigate the effect of time delay in the active interaction. In a similar experiment, Botvinick et al. reported that the proprioceptive drift deteriorates proportionally as the time delay of the tactile stimulation between the subject's hand and the fake limb increases [2]. However, the time delay for active interaction in RHI has not been investigated.

4.2.1 Experimental setup

Fourteen right-handed healthy subjects (including two females, aged 21–25 years) took part in the experiment. In this experiment, a time delay of 0 to 300 ms was artificially inserted into the control system. The experiments were conducted on each subject with time delays of 0, 50, 100, 150, and 300 ms in a random order. The other experimental conditions were configured based on condition (c) in the previous experiment. Note that the time delay due to the system configuration (mechanical and electrical) is 2 ms and is not included in the configured time delay. The questionnaire tests were also conducted after each trial, as described in the previous section.

4.2.2 Experimental results

Fig. 9 shows the experimental results for the proprioceptive drift for each condition. It is clearly shown that the time delay deteriorates the multisensory illusion. The proprioceptive drift significantly decreased for a time delay over 100 ms. This corresponds well to the studies on multisensory integration [23]. A further discussion is described in the last section. Note that the proprioceptive drift in the condition with no time delay is not identical to condition (c) in the previous experiment since these two cases have been conducted under different experimental setups (e.g., subject group and trial order).

The results of the questionnaire (as illustrated in Fig. 10) show a proportional decrease in the score as the time delay increased in Q1, Q2, and Q3. This fact corresponds to the proportional decrease in the proprioceptive drift for an increase in the time delay. Therefore, an adverse effect of the time delay on the multisensory illusion was also shown in the subjective assessment. From the questions on the unpredicted phenomena (Q4 and Q5), the scores were all low, which shows the validity of the experiment. Fig. 11 shows the computed illusion index for each condition, which can be given by averaging the score from the illusion statements (Q1–3) and control statements (Q4–5) of each

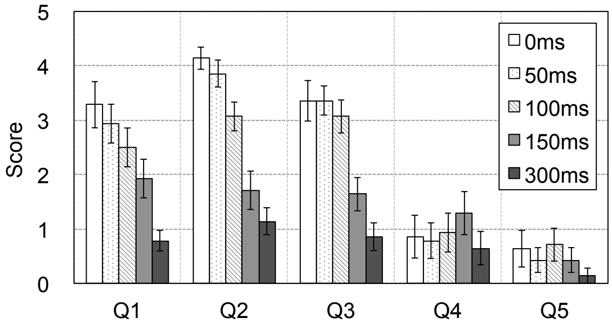

Fig. 10. The questionnaire results for the time delay experiment are shown. The score proportionally decreased as the time delay increased in Q1, Q2, and Q3. The bars and error bars indicate the mean value and standard error, respectively.

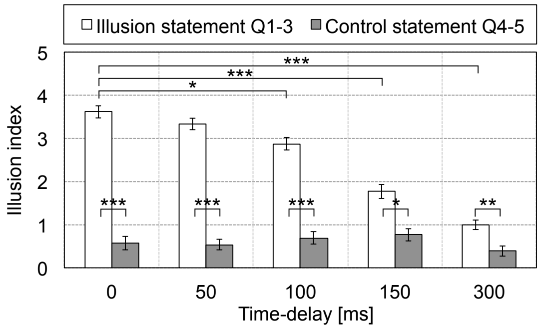

Fig. 11. The illusion index was computed by averaging the scores from the illusion statements (Q1–3) and control statements (Q4–5) of each subject. Significant differences were observed in all cases ($p<0.001$ ***, $p<0.01$ **, $p<0.05$ *, two-tailed paired samples t-test). The bars and error bars indicate the mean value and standard error, respectively.

subject. Although significant differences were observed in all cases between the illusion and control statements, the illusion index became lower at the longer time delay. Significant differences were observed between the illusion indexes for time delays of 0 and 100 ms, 0 and 150 ms, and 0 and 300 ms. This shows that a time delay over 100 ms significantly deteriorates the multisensory illusion on a subjective level. Therefore, the results of the questionnaire support the finding in the measurement of proprioceptive drift.

5 Conclusions and Discussions

To extend conventional RHI, we introduced robotic technology in the form of a 1 DOF master-slave system. The robotic instruments let us explore RHI in a new aspect: active interaction between the body and the fake limb. We thus investigated the effect of active interaction, such as active touch with a varied time delay in RHI.

The main contribution of the paper lies in finding that active touch causes an enhanced RHI. The results imply that an additional active component may enhance the RHI combined with passive touch even more; however, further experimentation is required to quantitatively assess this issue. Several important facts regarding this issue have been reported in the past. These include the sense of agency and the sense of body ownership [17]. Agency is the sense of intending and executing actions, including the feeling of controlling one's body movements and, through them, events in the external environment [18]. Body ownership refers to the sense that one's own body is the source of the sensations. The active touch using RH-MSS seems to largely involve agency since the robotic instruments let the subject perform the voluntary movement. Tsakiris et al. reported that agency may be expected to enhance the sense of body ownership since agency is responsible for the coherence of body ownership [19]. A similar finding of higher ratings in active conditions has been reported by Kalckert et al. [21]. Dummer et al. reported an interesting fact that when the subjects' active movements were used to induce an illusion of body ownership over a rubber hand, the illusion was stronger than when the movements were passively imposed [20]. These findings support the results that we showed in the experiments using RH-MSS. However, Walsh et al. have reported that the active movements produced an illusion that was the same or weaker than that produced by passive movements [16]. They described that the possible reason is the greater incongruence between the tactile and visual information in their experimental setup for the active condition. The robotic instrument introduced in this study has a major advantage in this point, and this may have influenced the discrepancy. Another important aspect is that the presented experiment involves active touch, that is, both movement and touch. Kalckert et al. have reported that the illusion arises not through the particular touch sensation but through the matching of the movement sensation and visual information [21]. Further investigation in this direction using our device is currently in planning.

The experimental results for the time delay showed that the time delay is significantly correlated with the effect of the multisensory illusion, and the effect significantly decreased over 100 ms of time delay. The results shown in this paper can potentially contribute to investigations of neural mechanisms in the field of neuroscience as well as the study of MSS in the field of robotics. An interesting fact reported by Blakemore et al. [24] states that the time delay of self-produced tactile stimulation induces a decrease in the level of sensory attenuation and an increase in tickliness. In their report, the range of inserted time delay that decreases the level of sensory attenuation corresponds well to our results. Shimada et al. reported that a temporal discrepancy of less than 300 ms between visual and tactile stimuli is preferable to induce a strong sensation of RHI

[25]. Our result implies that a further-enhanced illusion can be elicited by introducing active touch – and in this case, less than 100 ms of time delay is significantly effective. In addition, the time delay in MSS has been widely discussed in the field of robotics. These discussions have mainly been focused on the system stability and the system performance, such as the task completion time. In some of the past studies [26]–[29], it has been reported that the task completion time proportionally increases while increasing the time delay. An interesting fact is that a deterioration of multisensory illusion was observed for shorter time delays, such as 50–100 ms, compared to the past studies on MSS (generally tested for over 500 ms to several seconds). This implies that an ultimately intuitive MSS – such that the operator can manipulate the slave as part of his/her body – requires a much shorter time delay, as we showed in this study. Furthermore, the presented study can be linked to the studies on telepresence and embodiment [30] as well as virtual reality [31].

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