

# System to Induce and Measure Embodiment of an Artificial Hand with Programmable Convergent Visual and Tactile Stimuli

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**Abstract**— The sense of prosthesis embodiment, or the feeling that the device has been incorporated into a user's body image, may be enhanced by emerging technology such as invasive electrical stimulation for sensory feedback. In turn, prosthesis embodiment may be linked to increased prosthesis use and improved functional outcomes. We describe the development of a tool to assay artificial hand embodiment in a quantitative way in people with intact limbs, and characterize its operation. The system delivers temporally coordinated visual and tactile stimuli at a programmable latency while recording limb temperature. When programmed to deliver visual and tactile stimuli synchronously, recorded latency between the two was  $33 \pm 24$  ms in the final pilot subject. This system enables standardized assays of the conditions necessary for prosthesis embodiment.

## I. INTRODUCTION

Upper limb amputees' needs are not being met by existing prostheses, as evidenced by prosthesis rejection, non-wear [1], and user reports of restricted activities [2]. One approach to improving user experience and functionality with a prosthesis is the restoration of biomimetic sensory feedback [3-5]. In addition to the potential to improve functional ability [4-5] and decrease phantom limb pain [6-7], sensory feedback may lead to embodiment of the prosthesis, or the sense that the device is a part of the prosthesis user's body. Embodiment depends upon the integration of multiple sensory input streams, including visual, tactile, and proprioceptive [8-11]. Prosthesis users rely largely on visual feedback when using their prosthesis, so the addition of tactile feedback may increase the likelihood of embodying the prosthesis. Because embodiment of a prosthesis may lead to increased use, and prosthesis use leads to improved functional outcomes [12], it is important to determine the conditions necessary for prosthesis embodiment. We describe the development of a system designed to investigate these conditions, the MiHand (Multimodal Integrated Haptic Assay of Native limb Deception).

One commonly-used approach for studying embodiment is the rubber hand illusion [8], in which subjects are made to feel that an artificial hand belongs to them. This illusion is induced by touching the subject's own hand, which is hidden from view, while simultaneously touching an artificial hand the subject is watching. Most studies that employ the rubber

hand illusion use a human researcher to administer the dual stimuli [8-11], and therefore do not deliver stimuli with precise timing. However, timing has been shown to have an effect on the rubber hand illusion [9]. In other studies, precise timing control has been possible with the use of vibration stimulators [13]; however, these stimulators cannot mimic many types of incidental object contact.

Approaches used to identify the rubber hand illusion in previous experiments include questionnaire, proprioceptive drift [8], and limb temperature [14]. Proprioceptive drift measures a subject's perception that the location of the hand on the side experiencing the illusion migrates toward the artificial hand. Limb temperature decreases in the hand on the side experiencing the illusion.

Because embodiment may depend on temporal and spatial convergence of stimuli [15], we developed a system to induce the rubber hand illusion and measure the extent of the illusion. This system, the MiHand, was designed to deliver temporally coordinated stimuli at a predetermined latency and record the biosignal changes, such as temperature fluctuations, caused by the rubber hand illusion.

## II. METHODS

### A. Experimental Setup and System Integration

To test the MiHand system, subjects were seated at a table, with an artificial hand placed on the table next to the real hand. The real hand was obscured from a subject's line of sight by a platform covering it. The control hand was placed in view on the table. For example, if the artificial hand was the right hand as in Fig. 1, the artificial hand was placed to the immediate left of the real right hand. The real right hand was placed beneath a platform, and the real left hand was visible on the table. A drape covered both arms and the artificial hand's wrist terminus, leading to an immediate visual illusion of ownership because the artificial hand appeared as if it could be connected to the subject (Fig. 1).

LabVIEW (National Instruments Corporation) running on Windows 7 was used to control the experiment and record data through two DAQs (USB-6259 and USB-6009, National Instruments Corporation).

### B. Tactile and Visual Stimuli

To deliver convergent tactile and visual stimuli, the subject's hand and the artificial hand were tapped repeatedly during an experiment by two displacement sensors (8 mm stroke subminiature gauging Differential Variable Reluctance Transducers, LORD MicroStrain Sensing Systems, nominal resolution 2  $\mu$ m) mounted with custom-designed 3D-printed arms on separate stepper motors (ISM-7411E, National

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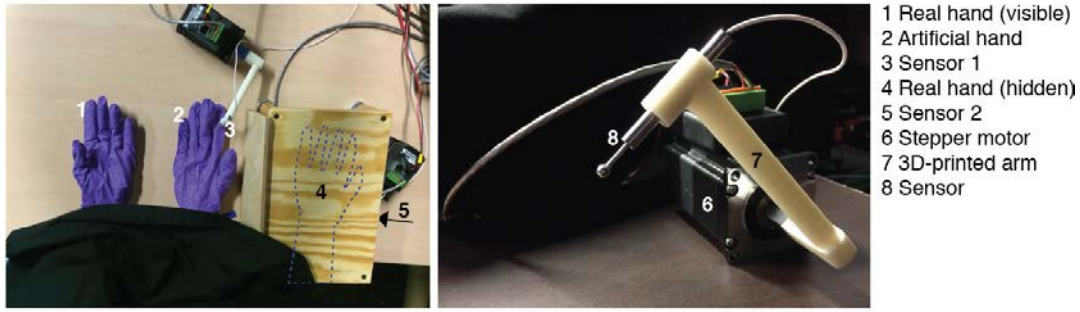


Figure 1. Experimental setup. The subject is seated at a table with a drape covering both arms, and wears nitrile gloves on both hands. A nitrile glove is also fitted on the artificial hand. Two motors drive displacement sensors to tap both the real and artificial hand synchronously.

Instruments Corporation). The displacement sensors were used to detect physical contact so that the latency between tactile stimulus (tapping subject's hidden hand) and visual stimulus (tapping artificial hand) can be controlled and varied in future experiments. Motor control and displacement sensing were routed through the USB-6259 DAQ, which had a sampling frequency of 10 kHz. Motor speed was 0.2 rev/s. Although the motors could be controlled via Ethernet connection to a LabVIEW port, in practice we found that latency to command execution via this port was unacceptably non-deterministic, sometimes resulting in differences of up to 1 second between real and artificial hand contact in the nominally synchronous tapping condition. Therefore, motors were controlled with onboard digital input terminals through the USB-6259 DAQ, which was connected to the PC via USB 2.0 for lower latency variation (less than 100 ms difference between contact with real and artificial hands in synchronous tapping condition).

Prior to each experiment, a calibration routine was used to set the initial positions of the displacement sensors appropriately to adjust the offsets in the control VI so that the desired temporal synchrony could be obtained. During calibration, 1 s of baseline signal was recorded from each displacement sensor while it was not contacting a hand. The two motors were then driven counterclockwise, bringing the sensors toward the real and artificial hands until they made contact. Contact was defined as a displacement reading of 10 mV above the maximum recorded baseline value. The contact position was recorded for use during the experiment, and both sensors were then rotated back clockwise away from the real and artificial hands by an equal amount, up to one quarter turn depending on the height of the box obscuring the subject's real hand. During this pilot study there was some variability in the height of this box.

The LabVIEW VI was used to set trial length and latency between contact of the artificial hand and contact of the hidden real hand. For system design and piloting, we report here on trials with a programmed latency of 0 ms.

### C. Measurement of Rubber Hand Illusion

We hypothesized based on previous reports [14] that the temperature of the hand on the side experiencing the illusion would drop as the artificial hand was embodied. Hand temperature was therefore recorded with thermistors (1 k $\Omega$  at 25  $^{\circ}$ C, Keystone Carbon Company) taped to the wrist, palm, or finger of each hand. A voltage divider with a 1 k $\Omega$  resistor was connected to the USB-6009 DAQ.

We hypothesized based on previous reports [8, 15] that subjects' perception of the location of the hand experiencing the illusion would shift toward the artificial hand as it was embodied. To test for this effect, we used an assay of proprioceptive drift both before and after the administration of convergent sensory input (a five-minute block of synchronized tapping on both the real and artificial hands). Briefly, both real hands and the artificial hand were covered to remove visual cues. As in [16], a number line was then placed across the table from the subject, and the subject was instructed to verbally indicate the location on the number line that was closest to the index finger on the right hand (the side experiencing the illusion). The position of the number line relative to the hands was shifted randomly for each proprioceptive drift measurement, so that the subject could not use previously reported numbers as anchor points.

Before the illusion was induced and following a trial, we asked subjects 2 and 3 seven questions from the rubber hand illusion questionnaire used by Kalckert, *et al.* (Table I) [15]. Questions 1-3 are intended to measure the strength of the embodiment, and questions 4-7 are intended to serve as a control to determine whether a subject is suggestible. Subjects responded to the question on a Likert scale from -3 (strongly disagree) to 3 (strongly agree).

### E. System Demonstration

All procedures were approved by the U.S. Food and Drug Administration Institutional Review Board, the Research Involving Human Subjects Committee. All subjects gave informed consent to participate in this research. Six subjects participated in this study during system design and piloting. Here we report on the final three subjects, for whom hand location, thermistor location, and proprioceptive drift approach were finalized. Subjects sat with both hands supinated, resting comfortably on a table. Thermistors were taped to the middle phalanges of each index finger, and subjects wore nitrile medical exam gloves on both hands.

TABLE I. RUBBER HAND ILLUSION STRENGTH QUESTIONNAIRE

Category	Question
Embodiment strength	1. I felt as if I was looking at my own hand
	2. I felt as if the rubber hand was part of my body
	3. I felt as if the rubber hand was my hand
Control	4. I felt as if my real hand were turning rubbery
	5. It seemed as if I had more than one right hand
	6. It appeared as if the rubber hand were drifting towards my real hand
	7. It felt as if I no longer had a right hand, as if my right hand had disappeared

Putting gloves on both real hands was found during pilot testing to increase verbal report of embodiment during the illusion. The artificial hand was also gloved for consistency. The real hand on the side designated to experience the illusion was obscured beneath a small platform that rested on the table. Subjects were draped with a black sheet across the shoulders, arms, and wrists of both hands and the artificial hand (Fig. 1), creating an immediate visual illusion that the artificial hand was the subject's real hand.

Subjects sat without moving for five minutes to record a temperature baseline. At this time, they also answered the proprioceptive drift question and the embodiment questionnaire for the first time. Next subjects were instructed to observe the visible hands (the artificial hand and their contralateral real hand) while the motors tapped synchronously on the distal phalanges of the hidden real and visible artificial index fingers for five minutes.

### III. RESULTS

#### A. Timing of Tactile and Visual Stimuli

The MiHand system delivered synchronous contacts, producing tactile stimuli to the hidden real hand synchronized with visual stimuli to the visible artificial hand. Between subjects 2 and 3, the control algorithm was revised to decrease latency variance. Table II gives the average latency and standard deviation between contacts for all subjects.

#### B. Temperature Response

Temperature response before and during the rubber hand illusion was highly variable, and better control of temperature or detrending of temperature data would seem to be the largest challenge to this measurement going forward. To control for fluctuations in body temperature, we report the ratio of the temperature of the hand on the side experiencing the illusion to the temperature of the control hand. Temperature ratio changed throughout the experiment, both before and during the rubber hand illusion. Fig. 2 shows this temperature ratio for the subjects who reported experiencing the rubber hand illusion, subjects 1 and 3. Both during baseline, when only a visual illusion of hand ownership was present, and during the rubber hand illusion, we observed temperature increases in the control hand that did not occur in the hand on the side experiencing the illusion (carets, Fig. 2). This phenomenon was therefore not associated with the convergent multimodal illusion, but may have been associated with the visual illusion.

#### C. Proprioceptive Drift

For the two subjects who reported experiencing the rubber hand illusion, there was an associated shift in the perception of the hand location toward the artificial hand. The

average length of the shift toward the artificial hand for these two subjects was 36 mm, and Table III shows the hand location as reported by each subject before the rubber hand illusion trial and immediately after the trial. This distance is consistent with other reports in the literature [16].

#### D. Questionnaire Responses

Subjects 2 and 3 answered questions from a standard rubber hand illusion questionnaire using a Likert scale. The questionnaire results mirrored the proprioceptive drift measure; subject 2 did not experience proprioceptive drift toward the artificial hand following the trial, and her answers to the questionnaire did not change. Because subject 2 responded with -3, or strongly disagree, to all questions both before and after the rubber hand illusion trial, only subject 3's average responses to the embodiment and control questions are shown in Fig. 3. This subject's responses indicate an increased sense of embodying the artificial hand due to the rubber hand illusion trial.

### IV. CONCLUSION

The MiHand system was developed to deliver tactile and visual stimuli at a known latency in a rubber hand illusion experiment, while recording associated biosignals that could be affected by the illusion. Here we tested only the 0 ms latency condition to test the system's ability to induce embodiment of an artificial hand. We found that the system was able to induce embodiment of the artificial hand in two subjects as measured by proprioceptive drift, or a shift in the sense of the hand's location toward an artificial hand. The proprioceptive drift results matched the results of a questionnaire about the sense of embodiment using a Likert scale, which was presented to two subjects. The subject who reported experiencing the conscious feeling of embodying the artificial limb had a proprioceptive drift toward the artificial limb, whereas the subject who did not report experiencing artificial limb embodiment did not have proprioceptive drift toward the artificial limb. Unstable baseline temperatures limit the interpretation of the temperature data.

Variance of the latency between tactile and visual stimuli was refined programmatically, so that the mean latency for the final subject was 33 ms for a programmed latency of 0 ms. This latency was due largely to gradual curling of the subject's hand over the course of the experiment, bringing

TABLE II. LATENCY BETWEEN TACTILE AND VISUAL STIMULI

Subject	Latency (mean $\pm$ s.d., ms)	Trial time (s)	Total stimuli
1	335 $\pm$ 145	308	73
2	173 $\pm$ 119	302	71
3	33 $\pm$ 24	301	76

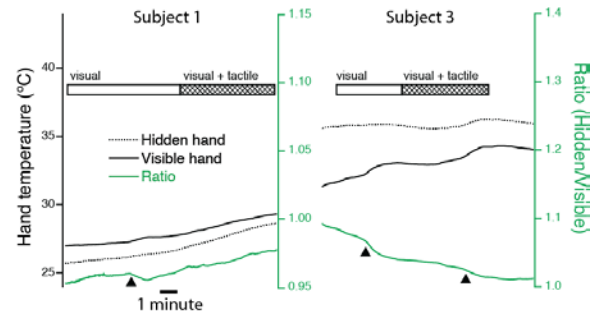


Figure 2. Limb temperature (left axis) and ratio of temperature of the hand on the side experiencing the illusion to control hand (right axis) as a function of time during the experiment for two subjects. Carets indicate temperature increases in the control hand that did not occur in the hand on the side experiencing the illusion.

TABLE III. PROPRIOCEPTIVE DRIFT FOLLOWING RUBBER HAND ILLUSION

Subject	Difference between initial perception of hand location and post-illusion perception (mm)
1	35 (toward artificial hand)
2	-28 (away from artificial hand)
3	37 (toward artificial hand)

the finger closer to the displacement sensor over time. To further decrease the latency, we will explore the possibility of a small stabilizer for the index finger, which will hold it in place during the experiment. Care will have to be taken to mirror any additional tactile sensations with visual parallels on the artificial hand.

Stability of the limb temperature was also a concern during this pilot, with large changes in limb temperature even in the absence of the rubber hand illusion. Subjects reported that they felt their real hand growing warmer, likely an effect of the box positioned to obscure it from view. To address this issue, a new box has been designed to cover the real, control, and artificial hands, so that both the subject's hands will experience the same air flow through the box. The box has a transparent section so that the control hand and artificial hand are both visible, and an opaque section so that the hand on the side experiencing the illusion is obscured, as in [16]. A new artificial hand that more closely resembles a real hand will also be used, so that nitrile gloves will not be needed to support the visual illusion.

There are several aspects of embodiment and the rubber hand illusion that may be tested using the MiHand system. By varying visual and tactile stimulus timing and location, and observing the resulting physiology and behavior, we aim to apply this system to quantitatively evaluate the sensory conditions that lead to incorporating an artificial limb into the body image. These constraints on visuotactile temporal latency and spatial similarity may inform design constraints for sensory prosthesis acceptance.

The MiHand control software (LabVIEW VI) and associated CAD design for the 3D-printed displacement sensor mount are available upon request.

#### DISCLAIMER

The mention of commercial products, their sources, or their use in connection with material reported herein is not to be construed as either an actual or implied endorsement of such products by the U.S. Department of Health and Human Services.

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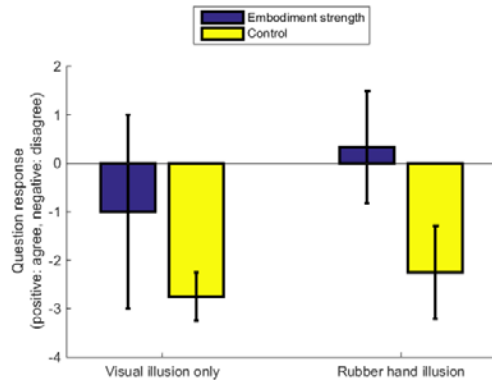


Figure 3. Questionnaire responses for subject 3 during visual illusion only and immediately following rubber hand illusion. Questions were answered on a Likert scale from -3 (strongly disagree) to 3 (strongly agree). Blue: answers to questions measuring embodiment strength; yellow: answers to control questions.

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