Systems for Identifying Design Constraints on Tactile Prosthetic Design

by Mahsa Alborz

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Thesis directed by

Heather Benz
Staff Fellow at U.S Food and Drug Administration

Chung-Hyuk Park
Assistant Professor of Biomedical Engineering

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Abstract of the Thesis

"Systems for Identifying Design constraints on Tactile Prosthetic Design"

The term embodiment refers to the sense of ownership of a body part. Although prosthetics can restore some function following limb loss, true embodiment remains elusive. This may be due to the absence of natural sensory feedback. Accordingly, new prosthetic systems that use electrical stimulation to provide this feedback hope to increase the sense of prosthesis embodiment.

To understand the input conditions necessary to induce embodiment, we have designed a system to induce embodiment effects using concurrent visual and tactile stimuli. A subject's real right hand and both upper arms are draped, and an artificial hand is placed on the table in front of the subject with the wrist end covered by the drape, creating a visual illusion that the artificial hand is connected to the subject's arm. Two stimulators are used to synchronously tap the hidden right hand and the visible artificial right hand, creating a "rubber hand illusion" [1]. Each stimulator consists of a programmable stepper motor (ISM-7411E, National Instrumentation Corporation) driving a displacement sensor (SG-DVRT-8, LORD MicroStrain Sensing Systems). To study the physiological response to the illusion, two temperature sensors were constructed, each using a voltage divider (one 2 kΩ thermistor from DigiKey and 1 kΩ resistor) attached to the middle phalanx of the index finger on both hands to monitor limb temperature. The temperature was recorded for five minutes of baseline (visual illusion only), five minutes during synchronous tapping (RHI), and five minutes after tapping stopped (post-RHI). Embodiment of the artificial hand was

then assessed using a standard RHI questionnaire and a proprioceptive drift assay, which registered the subject's perceived hand location.

The questionnaire responses of the subjects indicated that two of the three experienced the RHI. The subjects who experienced the RHI displayed proprioceptive drift, toward the artificial (visible) hand. Limb temperature has been shown to reflect the extent of prosthesis embodiment [2]. To control for temperature fluctuations, the temperature ratio of the RHI (right hand) to the control hand (left hand) was calculated. For the two subjects experiencing the illusion, we observed transient dips in the hidden/visible hand temperature ratio that were not time-locked to any particular stimuli.

In summary, the system successfully induced the RHI for two of three subjects, as evidenced by questionnaire results and proprioceptive drift. In future work, EEG signals will be recorded during the experiment and additional temperature sensors will be used to decrease the thermal variability.

Table of Contents

Abstract of Thesis iii

List of Figures vii

List of Tables viii

Chapter 1: Introduction 1

1.1 Novel upper limb prosthetics 1

1.1.1 Sensory feedback 4

1.1.2 Improved control using implanted electrodes 4

1.1.3 Virtual reality to study prosthesis 6

1.2 Studying Embodiment - Rubber Hand Illusion (RHI) 6

1.2.1 What is RHI? 6

1.2.2 Why study the embodiment? 8

1.2.3 How is embodiment measured? 9

1.2.3.1 Questionnaire 9

1.2.3.2 Proprioceptive drift 9

1.2.3.3 Limb temperature 10

1.2.3.4 EEG 11

1.2.4 RHI project aims 12

1.3 Virtual Reality (VR) 13

1.3.1 What is VR? 13

1.3.2 Why use VR in prosthesis prototype design and assessment? 13

1.3.3 What is measured in the VR? 14

1.3.4 Designed system's goals 15

Chapter 2: Methods 16

2.1 Embodiment 16

2.1.1 Materials 16

2.1.2 System development and design 17

2.1.2.1 Hardware 17

2.1.2.2 Software 24

2.1.3 Experiment Box 26

2.1.4 Collecting Proprioceptive drift 28

2.1.5 Collecting questionnaire data 29

2.1.6 EEG data 30

2.2 Virtual reality (VR) 31

2.2.1 Materials 31

2.2.2 System development and design 33

2.2.2.1 Hardware design 33

2.2.2.2 Software design 35

2.2.3 Experiment set up 36

2.2.3.1 Virtual reality version of task 2 36

2.2.3.2 Real world version of task 2 37

Chapter 3: Results and Discussion 39

3.1 Temperature data 39

3.2 Proprioceptive drift 40

3.3 Questionnaire responses 41

3.4 EEG future analysis 41

3.5 VR task 2: Sensory feedback 42

Chapter 4: Conclusion 45

4.1 Summary 45

4.2 Contribution to the Field 45

4.3 Future Studies 46

Chapter 5: Bibliography 47

List of Figures

Figure (1)- New prosthesis hand (DEKA arm) [7] 3

Figure (2) -The implant design [14] 5

Figure (3) - System set up [24] 12

Figure (4) – MuJoCo virtual reality [26] 14

Figure (5) – Stepper Motors 18

Figure (6) – Displacement sensor 18

Figure (7) – 3D printed arm [24] 19

Figure (8) – USB 6009 (top left) DAQ 6259 (top right) C-DAQ (Bottom left) NI-9201(Bottom right) 20

Figure (9) – Experiment box [27] 21

Figure (10)-EGI system 22

Figure (11) – Temperature sensors 23

Figure (12) – Embodiment system circuitry and connections 24

Figure (13) – Programming flowchart 26

Figure (14) – Experiment set up [24] 28

Figure (15) proprioceptive and the number line [28] 29

Figure (16) – Vibrating motor and Haptic motor controller 33

Figure (17) – Data glove 34

Figure (18) – Sensory feedback task interface 37

Figure (19) Limb temperature for two subjects experiencing RHI [24] 40

Figure (20) – The Questionnaire responses [24] 41

Figure (21) – EEG Future analysis 42

Figure (22) – VR sensory feedback task [30] 43

List of Tables

Table (1) – Embodiment experiment's materials 16

Table (2)- Rubber hand illusion strength questionnaire [24] 30

Table (3) – VR experiment's materials 31

Table (4) - Forces applied to the able-bodied palm using embodiment system 38

Table (5) – Proprioceptive drift results [24] 40

Chapter 1 – INTRODUCTION

1.1 Novel upper limb prosthetics

The DARPA HAPTIX program aimed to build prosthesis with tactile sensation for upper limb amputees' [3]. These new generations of prosthetic hands aim to fully restore the tactile sensation and function as a natural hand. Through the HAPTIX program DARPA has aimed to restore the tactile sensations of wounded service members and veterans. Various versions of a new tactile dexterous prosthetic, which builds upon the existing prostheses, are being designed and produced by different groups including universities and companies all across the Unites States [4].

It was stated by Doug Weber, DARPA program manager, in a DARPA press release, "DARPA is partnering with scientists at the Food and Drug Administration to help develop standards for verifying safety and quantifying benefits of this new class of advanced technologies. We hope to streamline the process of validating technologies that can help our military Service members and veterans who have been injured while serving our country." [4]. This type of research contributes to understanding of the benchmarks for a safe and effective prosthesis and constraints for prosthesis design.

Post-amputation peripheral and the central neural network and pathways are functional. Ideal hand prostheses should utilize that to reproduce the bidirectional link between the amputee's nervous system and the environment [5]. A group developed a non-invasive method using transcutaneous electrical nerve stimulation (TENS) to stimulate to induce

the sensation to the amputated arm [16]. Another research group exploited neural-machine interface to vibrate the muscles used for prosthetic control [6].

The work presented here includes two research projects that were designed to study new prostheses with tactile sensation. The first part of this thesis presents research on embodiment and the development of a system to induce embodiment in able-bodied individuals in order to understand its limits and constraints in prostheses design. The second part of this thesis describes MuJoCo HAPTIX which is a software test suite for tactile prostheses. MuJoCo includes a task in which participants report levels of sensation experienced. A system was designed to validate the MuJoCo task and also create a real world version of it.

Figure (1) New prosthesis hand (DEKA arm) [7]

1.1.1 Sensory Feedback

Receiving the sensory feedback from the prostheses can affect the user in several different ways. Experiencing the sensory feedback with the prostheses improves the user's experience and also increases the functionality of the artificial arm. [5-8]. Phantom limb pain occurs in case of limb loss and it is described as the sensation the amputees experience in the missing limb which can be experienced as pain or sensation. Prostheses with sensory feedback can also decrease phantom pain, which about 80% of amputees suffer from [9]. The tactile sensation, which is received by phantom limb, decreases the pain and also the uncomfortable phantom limb pain. In some studies the embodiment was used as a therapy for the phantom limb pain [10] .The studies show that experiencing the sensory feedback in the lost limb can decreases the phantom limb pain [11-12].

Sensory feedback provided by the prostheses can lead to the experience of embodiment or the sense that the prosthesis is part of the one's body [13]. The integration of multiple sensory inputs including, tactile, visual and proprioceptive can lead to the experience of embodiment. The embodiment of an artificial hand results as the effect of inter-sensory bias which is a class of perceptual effects [1]. The visuotactile stimulations correlated with the level that a rubber hand was embodied [13].

1.1.2 Improved control using implanted electrodes

In a haptic prostheses design, implanted nerve cuffs or clips are used to stimulate the nerves and, in most cases, the EMG signal from the muscles in order to control the limb.

The decoded signals from nerves or muscles drive the hand to perform the desired movement. The amputees have to go through the surgery for implanting the electrodes on the nerves or muscles.

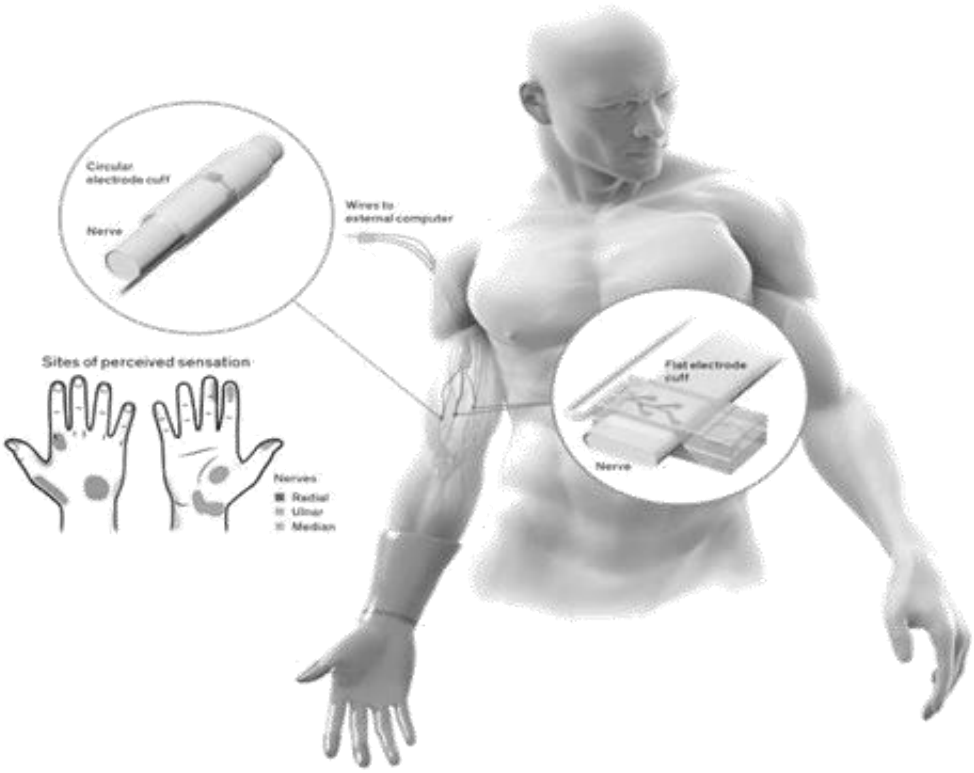

Figure (2) The implant design [14]

1.1.3 Virtual reality to study prosthesis

Sensate prostheses are expensive and not available in sufficient quantities for the many research groups studying prostheses control and feedback. Therefore, a virtual reality version of the prosthesis programmed to be used in the early studies and for training the amputees to use it. The virtual reality software called MuJoCo HAPTIX was designed and established for Roboti LLC. [15] This software is publicly accessible. The system used with our project coupled with the cyber glove (CyberGlove systems) and motion tracking system (OptiTrack) to track the fingers and also wrist movements.

1.2 Studying Embodiment

1.2.1 Rubber Hand Illusion (RHI) to induce embodiment

As it was referred to by Botvinick and Cohen in the Nature paper released in 1998; the rubber hand illusion (RHI) is having the illusion of that a rubber hand is the individuals hand. In this study they placed a rubber hand in place of the person's left hand and hided the person's real left hand. Then they simultaneously stroked the fake and real left hands. The person was staring at the rubber hand for 10 minutes while it was stroked by the brush. Then the participants were asked to report their experience and because of RHI, they felt that the rubber hand is their left hand [5].

RHI happens due to the intermodal matching of visual, tactile and proprioception.

This interaction between the senses can provide evidence as the basis for body-self-identification. As a result of RHI the people embodied the rubber hand and described the hand as their own hand. In this research, we used the RHI to induce embodiment of an artificial limb, so we can study the constraints of the prostheses design such as the latency between the visual and tactile sensation and the spatial matching between these two. In prostheses design it is essential to experience the temporal matching between the stimulation and touch perception. The latency between these two can interrupt the sensory feedback and therefore the embodiment of an artificial hand.

Moreover, the spatial matching of the touch and where it is felt an important factor, in experiencing the sensory feedback and inducing the embodiment. The rubber hand illusion (RHI) is a simple method for inducing embodiment of an artificial limb [1]. For this experiment the subject watches an artificial hand while their real hand is hidden. Both hands (the artificial and the hidden real hand) simultaneously receive tactile stimuli. In most studies the RHI is induced by a human researcher who delivers the stimuli synchronously to both hands, for example, by touching both the artificial and hidden real hand with paintbrushes on the index fingers. This can cause low precision in the timing of the stimuli. However, it has been shown that the timing of visual and tactile perception of the stimuli is an essential factor for inducing the sense of embodiment [17].

1.2.2 Why study embodiment?

Existing prostheses do not meet amputees' needs, as evidenced by the prostheses rejection, non-wear, or activity restrictions [18]. Currently available prostheses perform more as a tool for amputees to help them with their daily activities, however, by implementing embodiment into the new generation of prostheses the better functionality and wearing time of the prostheses can be achieved. Prosthesis, which do not feel like an attachment to the body and feel as it's an extension of one's body increase the use time and improve the functionality of the prostheses [19].

Also, restoration of sensory feedback may improve prosthesis functionality and encourage amputees to use prostheses [8-9]. Touch perception contributes to the sense of self and improves the communication and helps with the perception of the world [20]. Receiving the sensory feedback from the hand and finger can lead to the embodiment of the prosthesis and increase its functionality. Receiving sensory feedback from an artificial hand can lead to embodiment of the hand and feeling that the prosthesis is part of one's body [6].

1.2.3 How is embodiment measured?

To evaluate the embodiment of an artificial limb, thermal changes of the limb, standard questionnaire [21] and the proprioceptive drift that the subject perceives the limb to be located was considered. Thermal changes of the limb can be used as a marker for embodiment [2]. Another factor, which is widely used in the embodiment studies, is proprioceptive drift and it's used to quantitatively determine the perception of the prosthesis.

1.2.3.1 Limb temperature

It was previously reported that the limb temperature on the hand experiencing the embodiment would have variations [2]. After experiencing the embodiment, the limb temperature would drop on surface of the hand experiencing the illusion. The temperature drop is limb-specific. Embodying an artificial limb slows tactile information processing which leads to cooling the limb. This was also observed in people who lose the body ownership after the stroke [2]. In our study we measured the limb temperature to study the embodiment and determine any temperature variations due to the embodiment inducement.

1.2.3.2 Proprioceptive drift measurements

With reference to the previous studies [1, 21], as the subject embodies the artificial hand their perception of the hand experiencing the illusion shifts toward the artificial hand.

Feeling the touch and also visualizing it on the artificial hand cause the misallocating of the real hand. Therefore, without being able to visually determine where the hand that experienced the embodiment is, the subject will point closer to the embodied artificial hand. Proprioceptive drift was also used as a standard method in studying the embodiment and in previous RHI studies. In this study, it was used to evaluate the embodiment of the artificial hand by measuring how much the perception of the real hand moved toward the fake hand.

1.2.3.3 Electroencephalography (EEG)

Electroencephalography (EEG), refers to recording the brain signals. In general, EEG is usually recorded to understand and evaluate the brain performance due to certain phenomena. In many cases the EEG is recorded to study the brain and its changes after concussion. The changes in brain signals and specially the event-related potential (ERP) can be used to better understand the embodiment and how it alters the brain. ERP's are the brain responses to the sensory, cognitive and motor stimuli.

The ERP, which can be extracted from the raw EEG signals, are a most reliable non-invasive method to study the brain activity as a result of a sensory, cognitive or motor event [22]. Besides having good spatial resolution, the most desirable fact regarding the ERPs is having a high temporal resolution. Most of the brain activities happen in scale tens of milliseconds. ERP measurement enables us to study different brain activities in a factor of

one millisecond. Considering the nature of the brain activities and tissue characteristic there is no measurable conduction delay between generation of the brain activity and the recorded signals from scalp [23]. In our study we are designing a system to be able to record the EEG and the stimuli that the subject experiences at the simultaneously. This enables us to study the ERPs related to the time that the subject experienced the stimuli and learn about the electrophysiological changes in the brain when a person embodies an artificial hand.

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1.2.3.4 Standard Questionnaire

Questionnaire is a standard form of evaluating embodiment, which was used in previous studies of embodiment [1]. The standard questionnaire, which is commonly used for embodiment evaluation, is designed to evaluate the nine perceptual effect of embodiment. These nine perceptual effects are derived from the three-way interaction between vision, touch and proprioception [1]. The questionnaire was designed and first used in 1998 by Matthew Botvinick and Jonathan Cohen and was used since then to assess the embodiment of an artificial hand. In this study, we used a modified questionnaire as an approved and standard method to study the embodiment

1.2.4 RHI project aims

The goal for this project is to make a robust system that is able to induce embodiment. Besides inducing the embodiment of an artificial hand, the system should be able to record the real-time EEG and also the stimuli simultaneously and keeping track of the exact occurrence times. This system is aimed to be an easy-to-make system to induce and study different aspects of embodiment, which will be included in understanding and design of the prosthetics with sensory feedback. This system helps to understand the limits and constraints in designing and building prostheses that convey the embodiment.

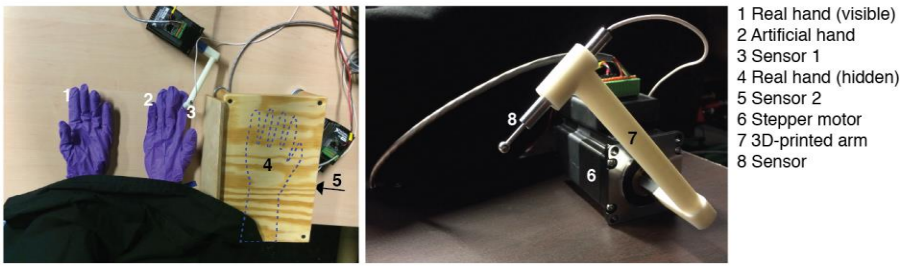


Figure (3)- System set up [24]

1.3 Virtual Reality (VR)

1.3.1 What is VR?

Virtual reality has many applications, from video games to science and research. Virtual reality is the virtual representation of the reality using computer. VR enables us to immerse an artificial model world and manipulate it directly. [25]

1.3.2 Why use VR in prosthesis prototype design and assessment?

In this project the virtual reality software were used to test and study the prosthesis with the sensory feedback. The virtual reality version of new prostheses was constructed to help studying and pointing the imperfections in the design. Having a virtual reality version of the prosthesis in the environment programmed as reality can help the engineers and researchers to understand the limits and also the features which should be included in the design of the prosthesis. In this project, a developed virtual reality of the prosthesis was used for the enabled bodied subject to manipulate certain tasks. Then the performance of them was evaluated and compared with the results from the real world (RW) version of the task developed for this project.

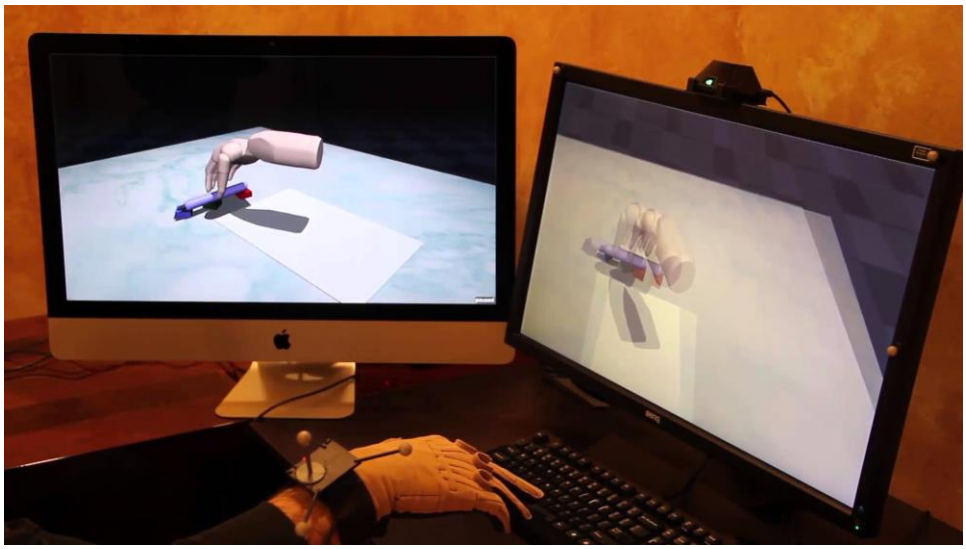


Figure (4) – MuJoCo virtual reality [26]

1.3.3 What is measured in the VR?

In the main study conducted at FDPU lab at FDA, the focus is on four different tasks. Each task designed to test a certain aspect of the prosthesis design and development. The first three tasks are designed to test the movement quality and control, quality of the sensory feedback and the combined use of movement control and sensory feedback. Task four on the other hand is functional performance outcome measurements assessment which is designed as an implementation of the Activities Measure for Upper Limb Amputees (AM-ULA). The performance data is available for the amputees which performed these tasks at University of Utah. To perform these tasks the individual with amputation used implanted EMG electrodes to control the virtual prosthesis and to receive stimulation from peripheral nerve implants to provide sensory feedback.

1.3.4 Designed system's goals

In this document we focus on the task two and evaluate the results from able-bodied subjects' performance and compare it to the same subjects RW results. In task two the subjects receive stimulations with various intensities and they have to report the intensity level of the stimulation they felt. We developed a system to deliver the same stimulations to able-bodied subjects in real world. The goal for this task is to validate VR system by comparing the able-bodied performance of task 2 in VR to RW equivalent task. This helps us to understand how realistic the sensory feedback is in the VR and also to improve the VR in order to transfer a better sensory feedback.

Chapter 2 – Methods

2.1 Embodiment

The embodiment design consists of two parts, the first one is the hardware design and second one is the software design. The hardware design includes designing the robotic arms that produce the stimulation, displacement sensors, a data acquiring system and EEG system. The software design enables all the parts to work together simultaneously and record the data accordingly.

2.1.1 Materials

Table (1) show the list of materials (hardware and software) used to design and develop the embodiment system.

Item no.	**Material**
1	Two Stepper motors (ISM-7411E, National Instrumentation Corp)
2	DAQ NI USB 6259 , USB 6009, C –DAQ module NI-9201
3	Displacement sensors (SG-DVRT-8, LORD MicroStrain Sensing Systems)
4	EEG system (EGI system with 64 electrodes)

5	Box with 2 parts: one opaque and one transparent side
6	Labview 2015 and Matlab 2016 with the parallel processing toolbox
7	Two laptops for controlling EGI system and robotic system
8	3D printed arms to connect displacement sensors to motors

Table (1) – Embodiment experiment's materials

2.1.2 System development and design

2.1.2.1 Hardware

The hardware is consisted of different parts that communicate with one another and operate at the same time.

1- Stepper Motors:

The stepper motors were manufactured by National Instruments (NI). Stepper motors were used for this project since precise movements desired. The two NI 7411E stepper motors can make the precise steps. Motors resolution is an important factor in generating accurate movements. Since the stepper motors have micro-stepping implemented in them for increasing the movement resolution. The motors used have 200 steps per revolution (full step) 400 steps per revolution (half step). This stepper motors have a feature called micro-step resolution which provide smooth movements.

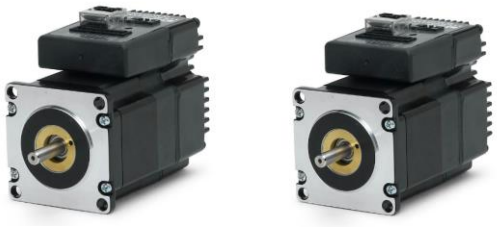


Figure (5) – Stepper Motors

2- Displacement sensors

Displacement sensors were used to deliver tactile sensation and measure latency between artificial and real hand touch. The sensors use a mechanical spring to measure the displacement related to the voltage change. To calibrate, the motor moves the arm, which the sensor is attached to, and it registers the touch as it contacts the subjects finger. Also, during the experiment the displacement sensors perform the stimulations by touching the index fingers simultaneously. The voltage changes and also the timing of the touches as detected by the voltage changes are recorded.

Figure (6) – Displacement sensor

3- 3D printed arms

The arms were designed to hold the displacement sensors and also connect it to the motors in a way that the motors can control the movements of the sensors during calibration and the experiment. The arms were designed with Solid works software and printed in 3D printing facility at FDA.

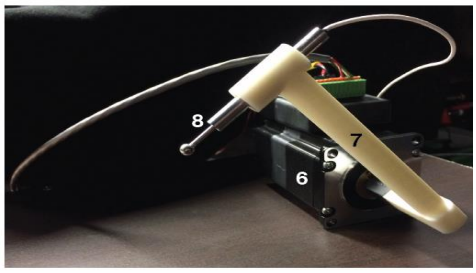


Figure (7) – 3D printed arm [24]

4- Data Acquisition System (DAQ-NI-USB 6259 and USB- 6009)

The National Instrument USB –6259, data acquisition system (DAQ) was used to run the system. The analog and digital inputs and outputs on the DAQ was used to send the commands from the coded program to the motors, displacement sensors and EGI system and also to record and restore the data from the displacement sensors using the coded program on the computer. Also, C-DAQ and NI-9201 was used to record the sync pulse from the EGI system. The USB-6009 was connected to the thermistors and directly to the computer in order to record the temperature.

Figure (8) – USB 6009 (top left) DAQ 6259 (top right) C-DAQ (Bottom left) NI-9201(Bottom right)

5- Experiment Box

The experiment box was designed to sit on the table in front of the subject in a way that a participant's hand, can be hidden under the opaque part of the box with one motor and displacement sensor located underneath and an artificial hand can be placed under the transparent part with a motor and displacement sensor. The box was designed with a moving cover and the opaque side and transparent side can be changed. This box was designed in the lab and manufactured in the machine shop at the FDA facility.

Figure (9) – Experiment box [27]

6- EEG system

The EEG system used in this experiment is manufactured by Electrical Geodesics Inc. (EGI). The EEG system consisted of a computer (MAC Pro) with the EGI software (Net Station 5.4 EEG Software) for data acquisition, the EEG cap and the amplifier. The system came with 3 sizes of EEG caps and each cap has 64 electrodes or channels which the head to record the brain activity at each electrode. To be able to record the brain activity during the embodiment experiment a sync pulse was generated and sent to the EGI system. The system can receive and records the pulse send to it and marks the triggers it receives. The triggers appear on the EEG data and then can be used to synchronize the EEG data with the data collected from the displacement sensors.

Figure (10)-EGI system

7- Thermistors

Hand temperature was recorded with thermistors (1 kΩ at 25 °C, Keystone Carbon Company) taped to the finger of each hand. A 1 kΩ resistor and thermistor were connected to the USB-6009 DAQ. The software was generated in Labview to record and calculate the temperature data.

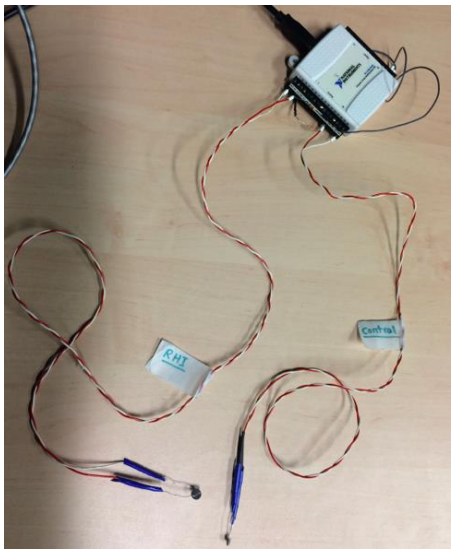


Figure (11) – Temperature sensors

8- Collecting temperature data

To collect temperature data, two thermistors were used and attached to the phalanx of the index fingers (right real and left real hands). The left finger's temperature variation was used as a control. A VI was programmed in Labview to collect the temperature data while the experiment was running. The temperature data then used to evaluate the embodiment as it was discussed before.

9- Embodiment System circuit design

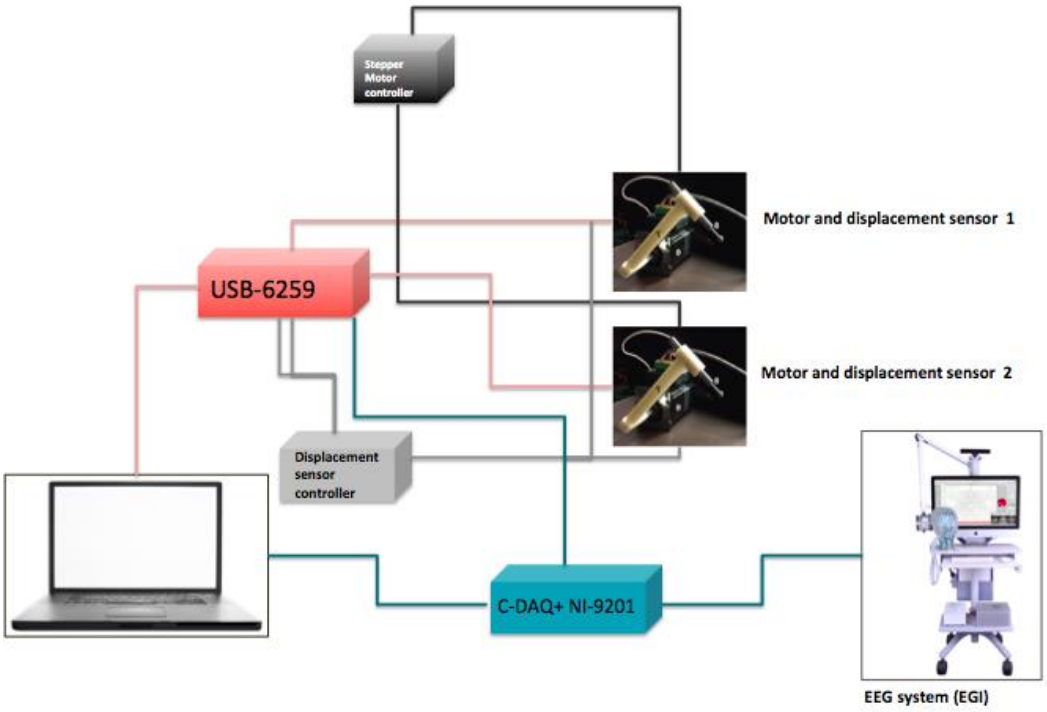


Figure (12) – Embodiment system circuitry and connections

2.1.2.2 Software

Labview 2015 and Matlab 2016 with the parallel processing toolbox were used to program the system. To control motors movements and also the communication between

systems the main programming part was done in Matlab. Labview visual interface programming (VI) was used to control the motors movements and also calibration. Then, the calibration VI and the VI for motors movement control was called by Matlab. The parallel processing tool was used in programming with Matlab to generate a sync pulse and send it to the EEG system while running the motors VI and recording the EEG data. Meanwhile, the displacement sensors data and the sync pulse reading were recorded. The sync pulse sent to the EEG system and read from the DAQ to enable us to match the timing of the EEG data and the displacement sensors. Since all the events should be synced the timing of the system is important and all the events should happen in parallel.

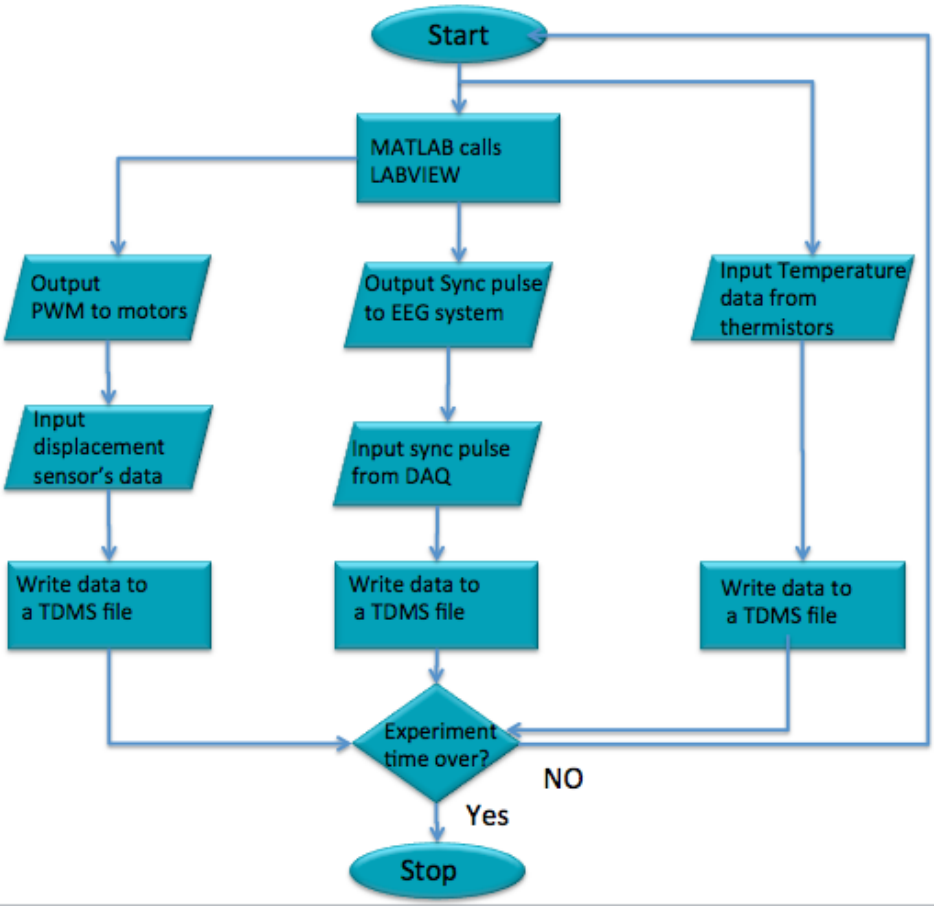


Figure (13) – Programming flowchart

2.1.3 Experiment set up

The set up for this experiment is as shown in figure (13). Subject's left hand and right hand are resting under the experiment box. The subject's right hand placed under the experiment box's opaque part and the left hand placed under the transparent part of the box. A faked hand with a glove was placed in between the right and left hand aligned with the subject's body. Two motors with the displacement sensors and 3D

printed arms were attached to them was placed close to the right real hand underneath the box and the fake right hand, in a way that the displacement sensors touch the index fingers. Then the subject's arms were draped covering the wrists of all hands, so that it appeared visually to the subject as if the fake hand were connected to the subject's body. The subject should look at the fake right and real left hand, during the whole experiment.

Session one of the experiment was the visual stimuli which the subjects sit in front of the experiment table with arms draped and only look at the fake hand while their real right hand was hidden under the opaque part of the experiment box. During these five minutes of visual stimuli the subjects responded to the embodiment questionnaire and proprioceptive drift for the first time. The second session of the experiment was the two motors tapping synchronously on the distal phalanges of the hidden real and visible artificial index fingers while recording the temperature data and displacement sensors data. The subjects instructed to look at the fake hand being tapped. In this session subjects experienced the visual and tactile stimuli. Then the subjects answered the embodiment questionnaire and the proprioceptive drift. The third session is the visual only for five minutes and the same as the first visual session the person was instructed to sit in front of the experiment set up and only looks at the visible hands.

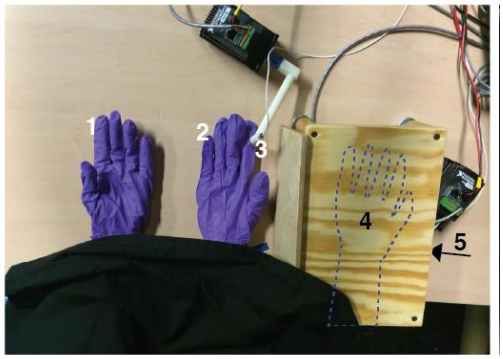


Figure (14) – Experiment set up [24]

2.1.4 Collecting Proprioceptive drift

Proprioceptive drift was performed in between the each session of the experiment (five-minute of continuous synchronized stimulation of both the real and artificial hands). After, first part of the experiment was performed the experiment set up was covered completely, covering both hand and motors, so the subject does not have the visual cues for the position of the hand. Also, a number line was placed across the table.

Then, subject was asked to look at a number line and report the location of the right hand's index finger. Then the distance from a reference point was measured and recorded. This information is important to evaluate how the perception of the hand changed after performing each session of the experiment. Number line's position was shifted in a random order so the subject could not use the previously reported numbers as a reference.

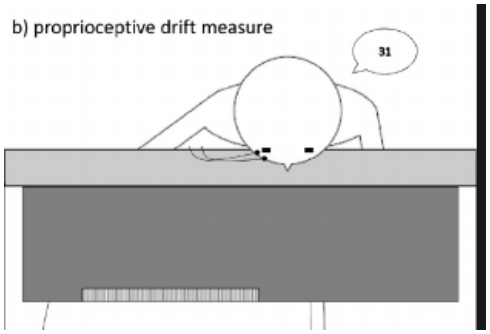


Figure (15) proprioceptive and the number line [28]

2.1.5 Collecting Questionnaire responses

Before the experiment and after each session a series of questions was asked to understand the level that the subject embodied the artificial hand. The modified Kalckert, et al. (Table 1) questionnaire was used to measure the level of embodiment [15]. The questions designed so that the questions 1-3 measuring the strength of the embodiment and questions 4-8 are used as a control to evaluate how much each subject can be influenced. The responses are based on Linkert scale –3(strongly disagree) to 3(strongly).

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 bod 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

Table (2). Rubber hand illusion strength questionnaire [24]

2.1.6 EEG data

The EGI system and the EEG cap with 64 electrodes were used to obtain the EEG information during the experiment. The EEG was reordered in order to study how experiencing the embodiment can affect the brain signals and to more understand this phenomenon. The EEG cap was prepared at the beginning of the experiment and placed on the subject's skull. The connections impendence with skull was checked using the EGI system software to ensure that there is enough conductivity between skull and electrodes.

2.2 Virtual Reality (VR)

The VR system used contains software and hardware as well. The VR software called MoJoCo which is stands for Multi-Joint dynamics (Roboti LLC.) with Contact. The VR system also contains a data glove, motion capturing system, vibro -motors and Arduino which will be explained in more details in this section

2.2.1 Materials

Item No.	**Description**
1	MuJoCo HAPTIXsoftware (Roboti LLC.)
2	Data glove (Cyber Glove systems LLC.)
3	Vibro-motors (Adafruit vibrating mini motors) and Haptic Motor Controller (DRV2605L)
5	Arduino (Arduino UNO)
6	Matlab code (Matlab 2016, Mathworks)

7	One embodiment motor and displacement sensor (see section 2.1.1)

Table (3) – VR experiment's materials

As it was shown in the table above the first and also the main part of the VR system is the software developed by Emo Todorov for Roboti LLC. This software was designed and developed to demonstrate some certain tasks, which are performed, by amputees and also able-bodied subjects. In our lab at FDA able-bodied people to generate normative data for comparison to data from amputees performed the tasks. This system also contains a data glove which is sensorized and communicating with the software. Another part of the system is a motion caption stand which was used to track the subject's wrist movements.

The vibro-motors from [Adafruit vibrating mini motors] was made and programmed to be use by Arduino. The purpose for making these vibro-motors was to be attached to the index finger and ring finger of the hand using the data glove to make the stimuli when a surface or an object is touched in the VR . The Arduino was used to program and work with the MujoCo software to make the vibration when the subject touches an object in the virtual environment.

A MATLAB code was developed and used the Embodiment system. The MATLAB code and embodiment system was used to perform the sensory feedback task in the VR, in real world and compare the results.

2.2.2 System development and design

2.2.2.1 Hardware design

In this document we are going to focus on the Vibro-motors and also the MATLAB code in Embodiment system, since this part was made and programmed for the purpose of this research presenting here.

1- Vibro-motors

Three Adafruit vibrating mini motors were used which was compatible with the Arduino to program and use for the experiment.

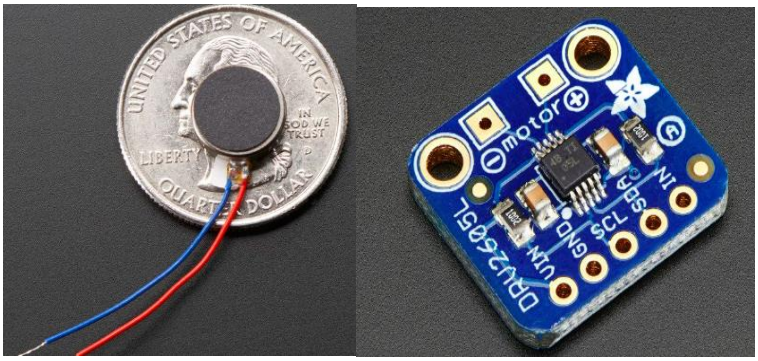


Figure (16) – Vibrating motor and Haptic motor controller

The mini vibro-Motors were connected to the Adafruit Haptic Motor Controller (DRV2605L). Then it was connected to the Arduino. The mini vibro-motors were placed on the tip of the ring, index and thumb fingers of the hand while wearing the data glove. Haptic controller was programmed so it vibrated anytime the subject touched an object in the virtual reality or to deliver the stimulation when it's necessary for the study.

2- Embodiment stepper motor and displacement sensor

From the embodiment experiment set up, one motor was used with the displacement sensor attached to the 3D printed arm. The embodiment system was used to generate the real-life version of the virtual reality task. The subjects performed the sensory feedback task in virtual reality and real-life.

3- Data glove

Data glove is a sensorized glove, which is able to communicate with the MoJoCo software. The data glove is connected to the computer with the MoJoCo software installed, through the USB cable and it also has control box connected to it to control the ON/OFF states of the glove.

Figure (17) – Data glove

2.2.2.2 Software design

The main software used for the VR system was the MoJoco software. Also, MATLAB code along with the LABVIEW virtual interface was used to control and perform the sensory feedback task, in real world.

Sensory feedback task: MATLAB code and Labview VI

MATLAB code was used to control the system to perform sensory feedback task in real world. The displacement sensor's depression registers by voltage changes. As the displacement sensor depressed the voltage drops. Sensory feedback task is the sensory feedback task and studies in what level an individual can discriminate different intensities of the stimuli. To generate different levels of stimuli (weak, medium, strong and very strong), a MATLAB code was composed that communicates with Labview VI, which controls the movements of the displacement sensor. The displacement sensors attached to the motors start moving toward the subject's index finger as Matlab and it stops moving as the voltage drops to the set value for that specific strength call it. For example, if the voltage drop required generating the medium intensity touch is -2.5v the motors with the displacement sensor attached to them will move forward until the voltage drop registered for the displacement sensor is -2.5v.

2.2.3 Experiment set up

2.2.3.1 Virtual reality version of sensory feedback task

The subject is sitting in front of the monitor wearing the data glove. Then calibration was performed to calibrate the VR system for the hand and finger movements of the subject. For the sensory feedback task, which is the focus of this document, the vibrating motors were attached to the tip of index finger and the palm of the hand. The calibration part for the stimuli includes delivering stimulation from (weak –very strong) and informing the subject of the intensity level of the stimulation. Then, random series of stimuli was generated and after stimulation the subject must report the intensity of it.

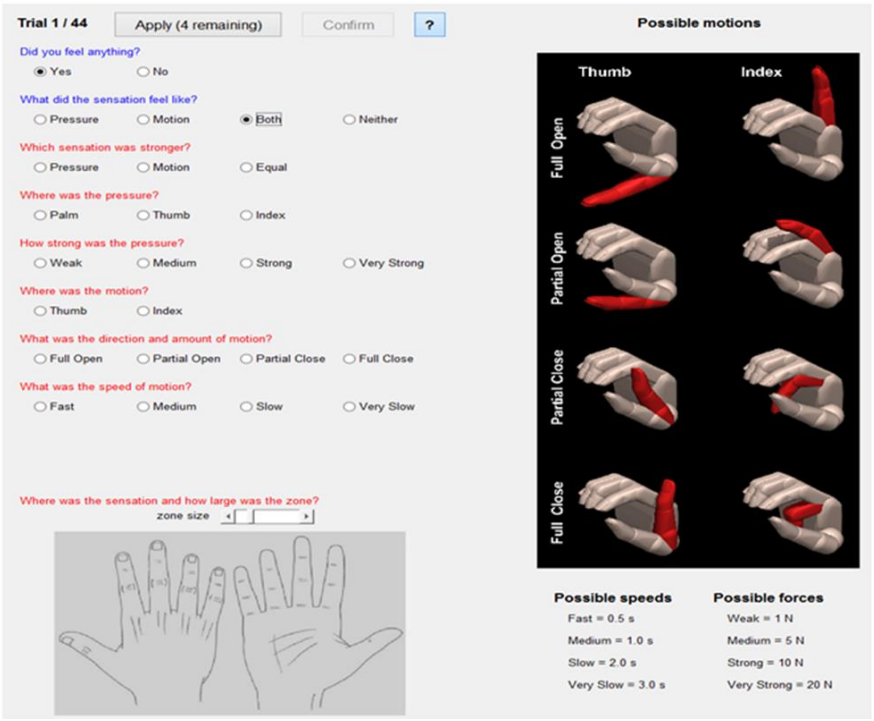


Figure (18) – Sensory feedback task interface

2.2.3.2 Real world version of sensory feedback task

With the embodiment set up, the hand that was used with the VR system was placed under the opaque part of the experiment box so the subject wasn't able to see the displacement sensor's depression. The displacement sensor attached to the stepper motor, was placed close to the hand so the displacement sensor is aligned with the palm. The calibration step performed with delivering different stimulations and informing the subject of the intensity level. The person preforming the test will randomly chose between different intensity levels of the stimuli. The hand that receives the stimuli hided under the opaque

part of the experiment box, the subject does not have any visual cue. The subject's response and the actual intensity of the stimulation were recorded.

Weak Avg. Force (N)	Medium Avg. Force (N)	Strong Avg. Force (N)	Very Strong Avg. Force (N)
0.50	1.20	1.85	1.94

Table (4) - Forces applied to the able-bodied palm using embodiment system

Chapter 3: Results and Discussion

The embodiment results presented in this part are from a preliminary version of the system. The second version of the embodiment system (hardware and software) was prepared to enable the EEG studies. For this study, three able-bodied subjects performed the embodiment experiment using the version one of the embodiment system.

3.1 Temperature data

As subjects 1 and 3 reported it, they experienced the embodiment. Limb temperature has been shown to reflect the extent of prosthesis embodiment [24]. To control for temperature fluctuations, the temperature ratio of the RHI hand (right hand) to the control hand (left hand) was calculated. According to the literature and previous research [2], It was expected to observe some temperature drop in due to embodying of the artificial hand.

The triangular markers on the plots show the temperature drop measured during the experiment for subject 1 and 3 (Figure 19). As it is shown in the plots the ratio of the hidden hand to the visible hand was dropped during the five minutes visual session of the experiment and for subject 3 during both visual and also visual+ tactile session. The subject 2 did not experience the embodiment and no evident change was observed in the temperature data and therefore, it wasn't included here.

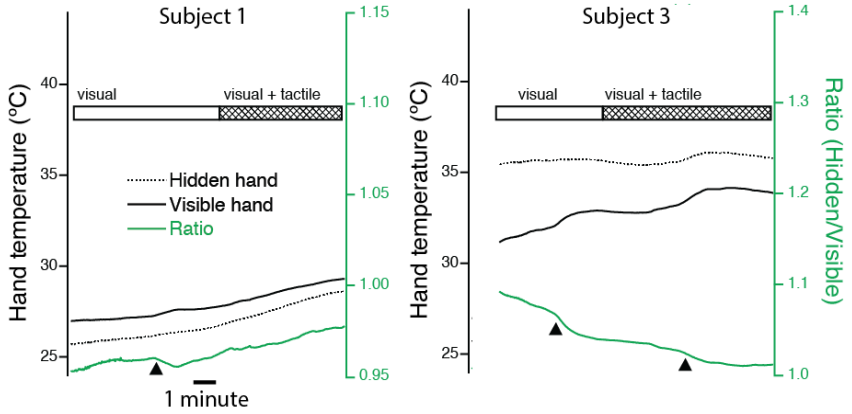


Figure (19) Limb temperature for two subjects experiencing RHI [24]

3.2 Proprioceptive drift

In Table (6) the proprioceptive results for three subjects is presented. The numbers were calculated by subtracting the initial perception of the hand location from the post-illusion perception. For subjects 1 and 3 who experienced the RHI the perception of the hand shifted toward the artificial hand, 35mm for subject 1 and 37mm for subject 3. However, for subject 2 did not experience the embodiment of the artificial hand and the perception of the hand moved away from the artificial hand by 28mm.

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)

Table (5) – Proprioceptive drift results [24]

3.3 Questionnaire responses

We expected the increase in positive responses (more positive responses) when the person embodies the hand comparing to the control data. The plot below shows that after rubber hand illusion induced the subject's positive responses to the questionnaire increased. During the only visual session of the experiment the responses was approximately -1.

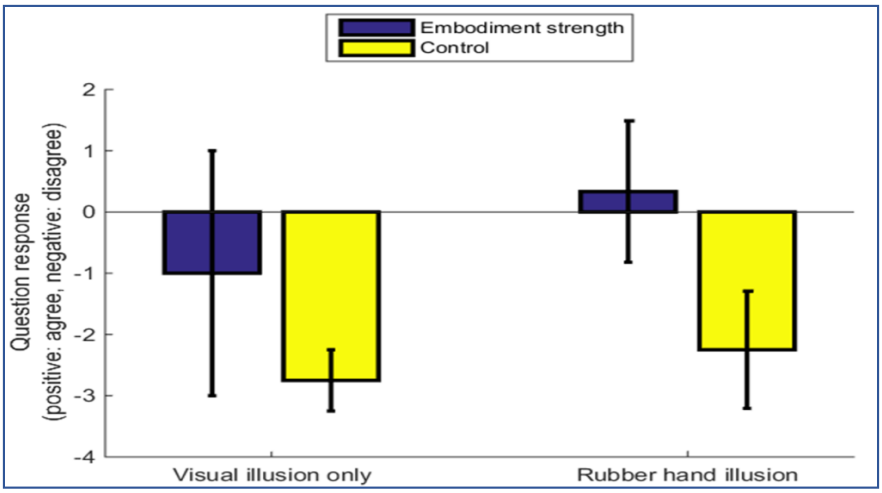


Figure (20) – The Questionnaire responses [24]

3.4 EEG future analysis

EEG data will be recorded from all subjects to investigate the neural correlates of embodiment during the RHI. Preliminary EEG data from one subject were collected. The synchronous tapping 0.006 ± 0.047 ms and asynchronous tapping which shows the latency between the taps of real hand and fake hand, was 97.016 ± 7.92 ms. ($n = 2311$ of synchronous and $n = 165$ of asynchronous taps; the system failed to record some taps.)

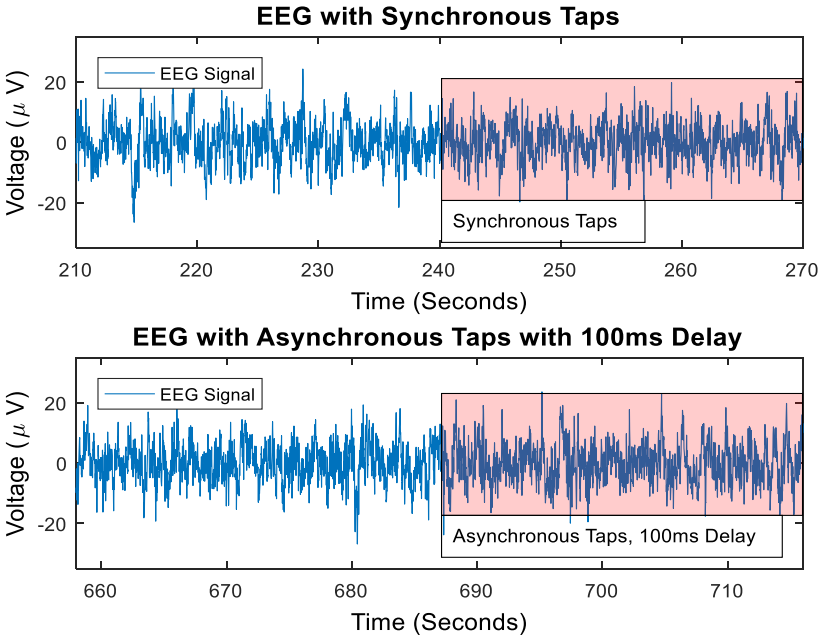


Figure (21) – EEG Future analysis

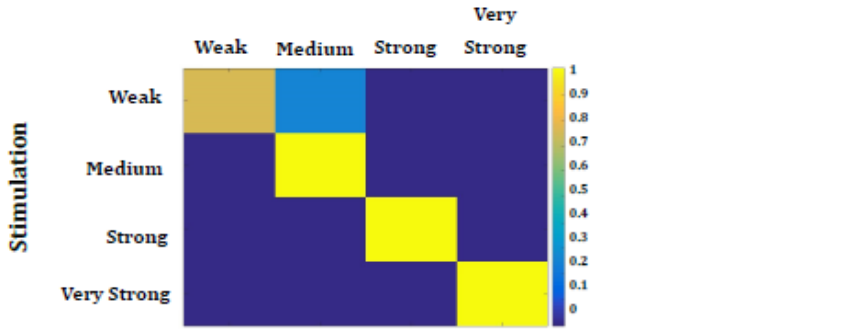
3.5 VR Sensory feedback task

The VR's sensory feedback task was performed by four able-bodied subjects (Figure 22 top). Then the results compared to the results acquired from same subjects performing the real-world version of the sensory feedback task (Figure 22 middle). The results from the one subject with implanted neural implants are presented in Figure (22 bottom).

All the subjects received the weak, medium, strong and very strong stimulations. The confusions matrices show in what extend the responses from the subjects matches the actual stimulation. For all correct answers to the stimulations, the diagonal rectangles value

is 1 (all yellow). As it can obtain from the confusion matrix, amputee wasn't very successful to distinguish between different stimulation intensities. However, the confusion matrix from the able-bodied subjects who received the vibrotactile stimulation shows better results from the same subjects performing the real-world version of the task. The able-bodied subjects also had the ability to predict the stimulation intensity. Form the results obtained for the able-bodied subjects, it can be concluded that the using the vibrotactile stimulation to simulate the sensory feedback may not provide a realist sensory feedback. For the real world version of the sensory feedback task it was more difficult for the subjects to detect the intensity level of the touch.

Task 2: Able-bodied Confusion Matrix of Vibrotactile Stimulated Touch Intensity



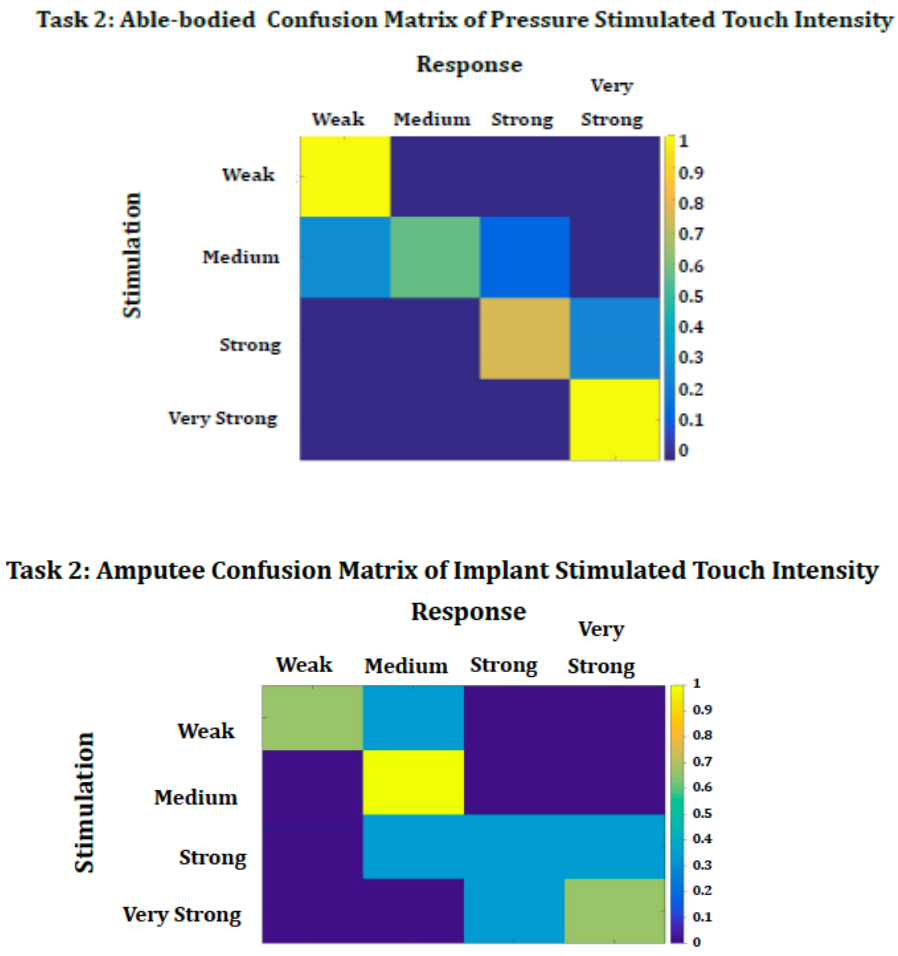


Figure (22) – VR sensory feedback task [30]

Chapter 4: Conclusion

4.1 Summary

The embodiment system was used to induce the embodiment of an artificial hand for three subjects. The temperature variation was used as an indicator of embodiment. The questionnaire and the proprioceptive drift assisted to measure the embodiment and also to compare it with the feeling reported by the subjects. As the subjects reported it and as it was concluded from the results, two of the subjects experienced the embodiment of and artificial hand. A new embodiment system was developed that enables synchronous EEG recording while performing the experiment.

To test the sensory feedback and to understand in what levels a subject is able to differentiate the intensity level of tactile stimulation, the VR test was performed using both displacement sensors attached to stepper motors and vibrating motors. The University of Utah performed the same test and Case Western Reserve University, for two amputees and the results were compared. According to the collected data both amputees and able-bodied subjects were able to distinguish different intensities of tactile stimulation.

4.2 Contribution to the Field

For designing and developing the prostheses, which functions as a natural hand, it may be a benefit of the system to promote acceptance of the prosthesis as part of the one's body. The embodiment of prosthesis can be induced by stimulating the peripheral nerves using neural implants to provide naturalistic tactile sensations. In the study presented in

this document a system was developed to induce the embodiment of an artificial hand to the able-bodied subjects. This system will be used as a tool to study the temporal matching and latency restrictions in the new prostheses design and development. And, it can help with evaluating these prostheses when they are available for mass production. Moreover, it was aimed to understand in what extend the spatial mismatch could still result in embodiment of the prostheses.

4.3 Future Studies

For the future studies, the EEG recording of the subject while performing the tasks will be used to understand the cortical representation of embodiment. Also, asynchronous tapping of the hand will be added to the system, so the subject can experience the delay between the visual and tactile stimulation. Understanding the physiologically acceptable latency between feeling a touch and seeing touch will be beneficial for the design of the prosthesis. Also, all the information and instructions regarding the system design and development will become available publicly to be used for the future studies in this field.

Chapter 5: Bibliography

[1] M. Botvinick and J. Cohen, "Rubber hands 'feel' touch that eyes see," Nature, vol. 391, pp.756-756, 1998.

[2] Moseley GL, Olthof N, Venema A, Don S, Wijers M, Gallace A, Spence C. Psychologically induced cooling of a specific body part caused by the illusory ownership of an artificial counterpart. Proceedings of the National Academy of Sciences. 2008;105(35):13169–13173

[3] "Hand Proprioception and Touch Interfaces (HAPTIX)." *Defense Advanced Research Projects Agency*, www.darpa.mil/program/hand-proprioception-and-touch-interfaces.

[4] "HAPTIX Starts Work to Provide Prosthetic Hands with Sense of Touch." *Defense Advanced Research Projects Agency*, www.darpa.mil/news-events/2015-02-08.

[5] S. Raspopovic, et al., "Restoring natural sensory feedback in real-time bidirectional hand prostheses," Science Translational Medicine, vol. 6, no. 222, 2014.

[6] Marasco, Paul D., et al. "Illusory movement perception improves motor control for prosthetic hands." *Science translational medicine* 10.432 (2018): eaao6990.

[7] Hruska, Joel. "FDA Approves the Deka Arm, the First Commercial Mind-Controlled Prosthetic Arm." *ExtremeTech*, 12 May 2014, www.extremetech.com/extreme/182202-fda-approves-the-deka-arm-the-first-commercial-mind-controlled-prosthetic-arm.

[8] Clark GA, et al. Engineering in Medicine and Biology Society (EMBC), 2014 36th Annual International Conference of the IEEE. IEEE; 2014. Using multiple high-count electrode arrays in human median and ulnar nerves to restore sensorimotor function after previous transradial amputation of the hand.

[9] Nikolajsen, Lone, and T. S. Jensen. "Phantom limb pain." British journal of anaesthesia 87.1 (2001): 107-116.

[10] V. S. Ramachandran and D. Rogers-Ramachandran, “Synaesthesia in phantom limbs induced with mirrors,” Proc. Biol. Sci., vol. 263, pp.377–386, 1996.

[11] P. M. Rossini, et al., “Double nerve intraneural interface implant on ahuman amputee for robotic hand control,” Clin. Neurophysiol., vol.121, pp. 777–783, 2010.

[12] Christian Antfolk, Marco D’Alonzo, Birgitta Rosén, Göran Lundborg, Fredrik Sebelius & Christian Cipriani (2014) Sensory feedback in upper limb prosthetics, Expert Review of Medical Devices, 10:1,45-54, DOI: 10.1586/erd.12.68

[13] M. Tsakiris and P. Haggard, “The rubber hand illusion revisited: visuotactile integration and self-attribution,” Journal of Experimental Psychology: Human Perception and Performance, vol. 31, no. 1, p.80, 2005.

[14] Tyler, Dustin J. “Creating a Prosthetic Hand That Can Feel.” IEEE Spectrum: Technology, Engineering, and Science News, IEEE Spectrum, 28 Apr. 2016, spectrum.ieee.org/biomedical/bionics/creating-a-prosthetic-hand-that-can-feel.

[15] Kumar, Vikash, and Emanuel Todorov. "MuJoCo HAPTIX: A virtual reality system for hand manipulation." *Humanoid Robots (Humanoids), 2015 IEEE-RAS 15th International Conference on*. IEEE, 2015.

[16] D’anna, Edoardo, et al. "A somatotopic bidirectional hand prosthesis with transcutaneous electrical nerve stimulation based sensory feedback." Scientific reports 7.1 (2017): 10930.

[17] H. H. Ehrsson, C. S. Henrik, and R. E. Passingham, "That's my hand!Activity in premotor cortex reflects feeling of ownership of a limb,"Science, vol. 305, no. 5685, pp. 875-877, 2004.

[18] Biddiss EA, Chau TT. Upper limb prosthesis use and abandonment: A survey of the last 25 years. Prosthet Orthot Int. 2007;31:236–257.

[19] Kejlaa GH. Consumer concerns and the functional value of prostheses to upper limb amputees. Prosthet Orthot Int. 1993;17(3):157–163

[20] D. W. Tan, et al., "A neural interface provides long-term stable natural touch perception," Science Translational Medicine, vol. 6, no. 257, 2014.

[21] A. Kalckert and H. H. Ehrsson, “Moving a rubber hand that feels likeyour own: a dissociation of ownership and agency,” Frontiers inhuman neuroscience, vol. 6, no. 40, pp.1-14, 2012.

[22] Woodman, G.F. Attention, Perception, & Psychophysics (2010) 72: 2031. https://doi.org/10.3758/BF03196680

[23] Nunez, Paul L., and Ramesh Srinivasan. Electric fields of the brain: the neurophysics of EEG. Oxford University Press, USA, 2006.

[24] Benz, Heather L., et al. "System to induce and measure embodiment of an artificial hand with programmable convergent visual and tactile stimuli." Engineering in Medicine and Biology Society (EMBC), 2016 IEEE 38th Annual International Conference of the. IEEE, 2016.

[25] Mazuryk, Tomasz, and Michael Gervautz. "Virtual reality history, applications, technology and future." (1996).

[26] VR hand manipulation with MuJoCo, https://www.youtube.com/watch?v=jZcY0QhLaL8

[27] Thakkar, Katharine N., et al. "Disturbances in body ownership in schizophrenia: evidence from the rubber hand illusion and case study of a spontaneous out-of-body experience." PloS one 6.10 (2011): e27089.

[28] Riemer, Martin, et al. "Defensive activation during the rubber hand illusion: Ownership versus proprioceptive drift." Biological psychology 109 (2015): 86-92.

[29] Tseng C, Chen P, Lee Y, Successful treatment of phantom limb pain and phantom limb sensation in the traumatic amputee using scalp acupuncture Acupuncture in Medicine 2014;32:356-358.

[30] Joyner,Janell , Quantitative virtual reality test platform for sensate prosthetic hands,

FDA research forum 2017.