



Design and Development of a Sensory Feedback System for Transradial Amputees using Body Powered Prostheses

by

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Abstract

Introduction Although significant advancements have been made in the realm of prosthesis design over the last two decades, amputees still reject their prostheses largely owing to the lack of sensory feedback received. The aim of this study was to develop a non-invasive sensory feedback system, including proprioceptive feedback, to work in conjunction with an existing body powered prosthesis that provides the user with increased tactile and proprioceptive awareness demonstrated in the form of improved results in an object identification and size discrimination (OISD) test, improved perceived confidence and improved response time.

Materials & Methods A sensory feedback system was developed using principles of rapid prototyping and testing. The system utilises capacitive sensors to mediate detection of proximity and touch, and makes use of a flex sensor to represent the position and motion of the finger digits of the prosthesis. A vibrotactile armband on the upper arm is used to feedback the sensed information to the user. Four able-bodied, adult volunteers participated in a preliminary study to test the efficacy of the capacitive sensor-vibrating motor disc combination. Five able-bodied, adult volunteers participated in a study conducted at the Medical Devices Lab at the University of Cape Town. The study investigated whether using the designed sensory feedback system in conjunction with a body powered prosthesis improves the participant's ability to locate and discriminate the size of spheres whilst visually and aurally restricted.

Results & Observations The results from the preliminary study show that all participants were able to distinguish between 3 levels of touch (proximity, light and hard touch) intensity and locate the position of the stimulation for good electrical conductors such as metal, human skin, wood and sometimes ceramic and glass materials depending on the coating. Results from the object identification test indicate that participants performed worse when no sensory feedback was provided (at an average accuracy of 0%). All participants were able to identify the objects accurately and efficiently when sensory feedback was provided at an average accuracy of 100%. Similarly, average accuracy for object discrimination improved from 58.33% with no sensory feedback to 85% with sensory feedback. Response times for both object identification tasks and size discrimination tasks also improved illustrated by a significantly negative relationship (negative gradient) in all trend lines over the period of testing. This suggests a learnability with the device: as the user becomes more cognisant of the device, the better their performance is in accuracy and response time. Confidence levels for size discrimination were highest with sensory feedback active. There was a significantly positive correlation (positive gradient) between accuracy and confidence. With no sensory feedback, confidence was on average 70% which increased to 84% with sensory feedback.

Conclusions The non-invasive sensory feedback system met all design requirements successfully. Future recommendations include minor adjustments to the design to optimise its capabilities after which, the design can be revalidated and tested on transradial amputees. Future work includes performing usability studies with amputee subjects, revalidation of the design through bench testing and with amputee subjects, and evaluating the scalability and manufacturability of the design with a variety of commercially available body powered prostheses.

Contents

| | | |
|----------|--|----------|
| 1 | Introduction | 1 |
| 1.1 | Problem Identification | 2 |
| 1.2 | Research Question, Hypothesis and Aim | 3 |
| 1.3 | Objectives | 3 |
| 1.4 | System Parameters Identification | 4 |
| 1.5 | Project Scope and Limitations | 5 |
| 1.6 | Dissertation Overview | 5 |
| 2 | Literature Review | 7 |
| 2.1 | Analysis of Disease State | 7 |
| 2.1.1 | Epidemiology | 7 |
| 2.1.2 | Physiological and Pathophysiological Overview | 9 |
| 2.1.3 | Overview of Amputations and Prosthetic Devices | 13 |
| 2.1.4 | Sensory Substitution | 19 |
| 2.2 | Modified Body Powered Prosthesis Overview | 25 |
| 2.3 | Existing Sensory Feedback System Solutions | 26 |
| 2.4 | Methods of Evaluation | 27 |

| | | |
|----------|---|-----------|
| 2.4.1 | Object Identification and Size Discrimination (OISD) Test | 27 |
| 3 | Design Methodology | 28 |
| 3.1 | Systems Overview and Design Process | 28 |
| 3.2 | Design of Functional Subsystems | 30 |
| 3.2.1 | Design Considerations and Requirements | 30 |
| 3.2.1.1 | Sensing Mechanism | 30 |
| 3.2.1.2 | Feedback Mechanism | 30 |
| 3.2.1.3 | Power Supply | 31 |
| 3.2.1.4 | Microcontroller Selection | 32 |
| 3.2.1.5 | Embodiment of System | 32 |
| 3.3 | Design Outcomes and Specifications | 34 |
| 3.3.1 | Sensing Mechanism: Touch and Proximity | 34 |
| 3.3.1.1 | Overview of Capacitive Sensors | 34 |
| 3.3.1.2 | Custom Capacitive Sensors | 36 |
| 3.3.2 | Sensing Mechanism: Position and Motion | 37 |
| 3.3.2.1 | Microcontroller | 38 |
| 3.3.2.2 | Power Supply | 39 |
| 3.3.3 | Embodiment of the System | 41 |
| 3.3.3.1 | Concept Generation and Selection | 41 |
| 3.3.3.2 | Final Embodiment of the Sensory System | 46 |
| 3.3.3.3 | Final Embodiment of the Feedback Mechanism | 52 |

| | | |
|----------|---|-----------|
| 3.3.4 | Preliminary Design Validation to Prove Proof-of-Concept of the Capacitive Sensor-Vibration Feedback Combination | 55 |
| 3.3.5 | Integrated System | 58 |
| 3.3.6 | Design Specifications | 63 |
| 4 | Design Validation | 68 |
| 4.1 | Failure Modes and Effects Analysis (FMEA) | 68 |
| 4.2 | Waterproof Validation | 70 |
| 4.3 | Power Consumption Validation | 71 |
| 4.4 | Participant Testing | 71 |
| 4.4.1 | Test Participants | 72 |
| 4.4.2 | Experimental Setup | 72 |
| 4.4.3 | Functional Tests | 74 |
| 4.4.4 | Procedure | 74 |
| 4.4.5 | Scoring System | 77 |
| 5 | Results and Analysis of Results | 78 |
| 5.1 | Objection Identification | 78 |
| 5.2 | Object Size Discrimination | 81 |
| 5.3 | Participant Confidence | 88 |
| 6 | Conclusions | 92 |
| 6.1 | Design | 92 |
| 6.2 | Design Validation | 93 |
| 6.2.1 | Sensory Feedback Improves Object Identification Accuracy | 93 |

| | | |
|----------|---|-----------|
| 6.2.2 | Sensory Feedback Improves Object Size Discrimination Accuracy . . . | 93 |
| 6.2.3 | Sensory Feedback Reduces Response Time in Execution of Tasks . . . | 94 |
| 6.2.4 | Sensory Feedback Improves Participant Confidence Levels | 95 |
| 6.2.5 | Overall Outcome | 95 |
| 7 | Recommendations and Future Work | 96 |
| 7.1 | Design Recommendations | 96 |
| 7.2 | Future Work | 97 |
| | Bibliography | 98 |
| A.1 | Flex Sensor Datasheet | 104 |
| A.2 | Important Information for Arduino Pro Mini | 107 |
| A.3 | Electronic Schematic of PCB for Sensory Feedback System | 109 |
| A.4 | Arduino Code for Sensory Feedback System | 111 |
| A.5 | Raw Data from Sensor-Motor Combination Testing | 119 |
| A.6 | HREC Formal Approval for Ethics | 124 |
| A.7 | Failure Modes and Effects Analysis | 127 |
| A.7.1 | Risk Analysis | 127 |
| A.7.2 | Risk Control Measures | 131 |
| A.8 | Raw Data from Participant Testing | 135 |

List of Figures

| | | |
|-----|--|----|
| 1.1 | Overview of Dissertation. | 6 |
| 2.1 | Sensory Transduction and Proprioceptors (MediaLook, 2017). | 10 |
| 2.2 | The Skin and its Sensory Receptors (Nature, 2019). | 12 |
| 2.3 | Types of Upper Limb Amputations (Du Plessis Orthotics & Prosthetics, 2021). | 14 |
| 2.4 | ADL arm Designed, Developed and Preliminarily Tested by Lara Timm (Timm et al., 2019) | 25 |
| 3.1 | Systems Overview of the Sensory Feedback System. | 29 |
| 3.2 | Design Process Followed. | 29 |
| 3.3 | Different Vibrational Arrangements Examined in the Study by Guemann et al. (2020). | 31 |
| 3.4 | Parallel Plate Capacitor (SparkFun, 2021). | 35 |
| 3.5 | Electric Field of a Parallel Plate Capacitor (Texas Instruments, 2014). | 36 |
| 3.6 | Image of Custom Capacitive Sensors Made with Copper Tape. Bottom Left: Sensor Without Embedding, Far Right: Sensor Embedded in 3D Printed Material, Top Left: Sensor Embedded in Silicone. | 37 |
| 3.7 | Flex Sensor Used to Determine Position and Motion of the Fingers of the Prosthesis (SpectraSymbol, 2014). | 38 |
| 3.8 | An Arduino Pro Mini 328 3.3V/8MHz (SparkFun, 2021). | 38 |
| 3.9 | An Arduino Pro Mini Pin Diagram (Components 101, 2020). | 39 |

| | | |
|------|---|----|
| 3.10 | 3.7 V Lithium Polymer 2500 mAh Rechargeable Battery. | 41 |
| 3.11 | Concept Ideas Generated for the Embodiment of the System. | 42 |
| 3.12 | CAD Image of the Concept for a Silicone Glove (Capacitive Sensors in Copper). | 44 |
| 3.13 | CAD Image of the Concept for a Silicone Glove (Capacitive Sensors in Copper) (Side View). | 45 |
| 3.14 | CAD Image of the Concept for a Synthetic Glove (Capacitive Sensors in Purple). | 45 |
| 3.15 | CAD Image of the Concept for a Synthetic Glove (Capacitive Sensors in Purple) (Side View). | 45 |
| 3.16 | CAD Image of the Concept for a Soft Exoskeleton (Capacitive Sensors in Copper)). | 45 |
| 3.17 | Design Iterations for the Flex Sensor Embodiment (Left to Right: 1, 2, 3, 4, 5, and 6 (final)). | 50 |
| 3.18 | Close-up of Design Iterations 5 (Left) and 6 (Right). | 51 |
| 3.19 | Finger Extension of Prosthesis without Flex Sensor Embodiment (Left) and with Flex Sensor Embodiment (Right). | 51 |
| 3.20 | Finger Extension of Prosthesis without Flex Sensor Embodiment (Left) and with Flex Sensor Embodiment (Right). | 51 |
| 3.21 | Front View of Vibrotactile Armband. | 52 |
| 3.22 | Back View of Vibrotactile Armband. | 52 |
| 3.23 | Vibrotactile Armband on Participant Upper Arm. | 52 |
| 3.24 | Front Image of the Design Iterations for the Haptic Enclosure (Left to Right: Iteration 1, 2, 3 and 4). | 53 |
| 3.25 | Front Image of the Design Iterations for the Haptic Enclosure with Haptics Inserted (Left to Right: Iteration 1, 2, 3 and 4). | 53 |
| 3.26 | Side Image of the Design Iterations for the Haptic Enclosure (Left to Right: Iteration 1, 2, 3 and 4). | 53 |

| | | |
|------|---|----|
| 3.27 | Capacitive Sensors Embedded within Silicone Placed on the 3D Printed Static Prosthetic Hand. | 56 |
| 3.28 | Velco Finger Straps with Vibration Motor Discs Inside and LEDs. | 56 |
| 3.29 | Materials used for Testing. | 57 |
| 3.30 | CAD Image of the Front of PCB. | 58 |
| 3.31 | CAD Image of the Back of PCB. | 59 |
| 3.32 | Front Image of Physical PCB used for Prototyping. | 59 |
| 3.33 | Image of Physical PCB used for Prototyping. | 59 |
| 3.34 | CAD of Electronic Housing (Left: Box, Right: Lid). | 60 |
| 3.35 | Longitudinal Section of the Embodiment to Illustrate the Embedded Capacitive Sensors (Copper). | 61 |
| 3.36 | Program Flowchart for Sensory Feedback System. | 62 |
| 3.37 | Program Function Flowchart for Haptic Intensity for: Capacitive Sensors (Left) and Flex Sensor (Right). | 62 |
| 3.38 | Complete Integrated Closed-Loop Sensory Feedback System (Palm View). | 63 |
| 3.39 | Complete Integrated Closed-Loop Sensory Feedback System (Dorsum View). | 63 |
| 4.1 | Tissue Paper Placement during Embedding Process for Dorsum Sensor. | 70 |
| 4.2 | Tissue Paper Removal after Water Test. | 70 |
| 4.3 | Tissue Paper before (Left) Water Test and after (Right). | 71 |
| 4.4 | Metal Spheres used for Testing (Left to Right: Large, Medium and Small). | 73 |
| 4.5 | Placement of Haptics on Participants (Image Adapted from Clinical Gate (2021)). | 73 |
| 4.6 | Sensory Feedback System on Participant (Left: Fully Extended, Right: Fully Flexed Grasping a Sphere). | 76 |

| | | |
|------|---|----|
| 4.7 | Sensory Feedback System on Participant Grasping a Sphere. | 76 |
| 5.1 | Response Time as a Function of Trial Number (0 to 12) for Participant 5. | 79 |
| 5.2 | Response Time as a Function of Trial Number (0 to 12) for Participant 1 to 4. | 80 |
| 5.3 | Average Response Time for All Participants as a Function of Trial Number (0 to 12). | 81 |
| 5.4 | Comparison of Participant Accuracy in Size Discrimination Tasks (No Sensory Feedback). | 81 |
| 5.5 | Comparison of Participant Accuracy in Size Discrimination Tasks (Sensory Feedback). | 82 |
| 5.6 | Comparison of Average Participant Accuracy in All Size Discrimination Tasks for Different Conditions. | 82 |
| 5.7 | Comparison of Average Participant Accuracy in Size Discrimination Tasks for Different Conditions. | 83 |
| 5.8 | Comparison of Participant Average Accuracy in Size Discrimination. | 85 |
| 5.9 | Average Response Time for All Participants for Size Discrimination as a Function of Trial Number (0 to 12). | 86 |
| 5.10 | Response Time for Size Discrimination as a Function of Trial Number (0 to 12) for Participant 1 to 4. | 87 |
| 5.11 | Response Time for Size Discrimination as a Function of Trial Number (0 to 12) for Participant 5. | 88 |
| 5.12 | Average Confidence Levels for All Participants for Size Discrimination Tasks as a Function of Feedback. | 88 |
| 5.13 | Average Confidence Levels of All Participants for Size Discrimination as a Function of Average Accuracy for Sensory Feedback (Blue) and No Sensory Feedback (Orange). | 89 |
| 5.14 | Average Confidence Levels for Each Participant for Size Discrimination Tasks with Sensory Feedback. | 90 |
| 5.15 | Average Confidence Levels and Average Accuracy Levels of All Participants as a Function of Size Discrimination Arrangement. | 91 |

| | | |
|---|---|-----|
| 1 | Participant Age and Upper Arm Diameter. | 135 |
| 2 | No Sensory Feedback (Part 1). | 136 |
| 3 | No Sensory Feedback (Part 2). | 137 |
| 4 | Sensory Feedback (Part 1). | 138 |
| 5 | Sensory Feedback (Part 2). | 139 |

List of Tables

- 2.1 Global and South African Population Distribution of Amputees (Maurice LeBlanc, 2018). 8
- 2.2 A Summary of the Three Main Proprioceptors in the Body (Core Walking, 2019; Biga et al., 2018). 11
- 2.3 Sensory Receptors found in the Skin (Categorised by Type of Stimulus Sensed) (Nature, 2019). 11
- 2.4 Types of Upper Limb Amputations (Hanger Clinic, 2019) 14
- 2.5 Summary of the Categories of Upper Limb Prosthetic Devices. \$ indicates up to \$ 4000 , \$\$ can range between \$ 4000 to \$ 10 000, \$\$\$ can range between \$ 25 000 to \$ 75 000. 15
- 2.5 Summary of the Categories of Upper Limb Prosthetic Devices. \$ indicates up to \$ 4000 , \$\$ can range between \$ 4000 to \$ 10 000, \$\$\$ can range between \$ 25 000 to \$ 75 000. 16
- 2.5 Summary of the Categories of Upper Limb Prosthetic Devices. \$ indicates up to \$ 4000 , \$\$ can range between \$ 4000 to \$ 10 000, \$\$\$ can range between \$ 25 000 to \$ 75 000. 17
- 2.5 Summary of the Categories of Upper Limb Prosthetic Devices. \$ indicates up to \$ 4000 , \$\$ can range between \$ 4000 to \$ 10 000, \$\$\$ can range between \$ 25 000 to \$ 75 000. 18
- 2.6 A Summary of Some of the Methods of Sensory Substitution. 19
- 2.7 Summary of Some of the Existing Solutions. 26
- 3.1 Power Consumption of the Sensory Feedback System. 40

| | | |
|-----|--|----|
| 3.2 | Evaluation of Remaining Concept Parameters for the Embodiment of the System | 43 |
| 3.3 | Review of the Design Iterations for the Flex Sensor Embodiment. | 47 |
| 3.3 | Review of the Design Iterations for the Flex Sensor Embodiment. | 48 |
| 3.3 | Review of the Design Iterations for the Flex Sensor Embodiment. | 49 |
| 3.3 | Review of the Design Iterations for the Flex Sensor Embodiment. | 50 |
| 3.4 | Review of the Design Iterations for the Haptic Enclosure. | 54 |
| 3.5 | Summary of Design Specifications of the Sensory Feedback System. | 64 |
| 3.5 | Summary of Design Specifications of the Sensory Feedback System. | 65 |
| 3.5 | Summary of Design Specifications of the Sensory Feedback System. | 66 |
| 3.5 | Summary of Design Specifications of the Sensory Feedback System. | 67 |
| 4.1 | Severity Value Associated with a Risk. | 69 |
| 4.2 | Occurrence Value (Probability) Associated with a Risk. | 69 |
| 4.3 | Risk Evaluation Matrix used to Evaluate Hazards. | 69 |
| 4.4 | Scoring Template for Each Participant (Repeated for a Sensory Feedback System and No Sensory Feedback System). | 77 |

List of Acronyms and Symbols

| | |
|----------------|---|
| ABS | Acrylonitrile Butadiene Styrene |
| ADL | Activities of Daily Living |
| CAD | Computer Aided Design |
| CLD | Congenital Limb Deficiency |
| CNS | Central Nervous System |
| EMG | Electromyography |
| FMEA | Failure Modes and Effects Analysis |
| HREC | Human Research Ethics Committee |
| JND | Just Noticeable Difference |
| L | Large |
| Li-Poly | Lithium-Polymer |
| M | Medium |
| OT | Occupational Therapist |
| OISD | Object Identification and Size Discrimination |
| PCB | Printed Circuit Board |
| PLA | Polyactic Acid |
| PNS | Peripheral Nervous System |
| S | Small |
| TPU | Thermoplastic Polyurethane |
| US | United States |
| VS | Voluntary-Closing |

Chapter 1

Introduction

The value of arms, hands and fingers are only realised when someone loses them and in the process loses the dexterity to perform activities of daily living (ADL). Acquired limb loss and congenital limb deficiency have a profound and long term impact on the lives of the patients. Not only will this affect a patient's physiological aspect of life but it will alter their social, occupational, financial, psychological and recreational aspects of life, too. For upper limb amputees, the combined experience of a loss of functional capabilities, loss of sensory connection and loss of human appearance together with the inability to easily conceal the amputated limb results in further psychological trauma (Ritchie et al., 2011; Antfolk, 2013).

Amputation is the removal of a limb or part thereof due to injury, disease or surgery (The Cape Amputee Clinic, 2014). The nervous system is made up of sensory and motor nerves which are used for rapid communication to and from the brain (Walker, 2014). The amputation of a limb results a disconnection of the nerves in the skin responsible for sensory-motor feedback from the amputated region; thus, sensory feedback ceases to exist in the amputated region. It is not reinstated in the affected limb once a prosthesis is fitted as they do not rejuvenate or replace the nerves (Treacy, 2018). Amputees that return to an independent lifestyle are able to do so by learning to adapt and by paying close attention to what they are doing. Thus, the user is required to exert significantly more cognitive efforts to do basic gestures and ADL which has contributed to the high rejection rate amongst active prosthesis users (Stephens-Fripp, Alici, & Mutlu, 2018; Alva, Muceli, Atashzar, William & Farina, 2020).

Without sensory feedback received from muscles, one is unable to monitor, control and correct one's paths of motion (Walker, 2014; Alva et al., 2020). Results from numerous

studies indicate that sensory feedback increases the user's inclination to wear the prosthesis, to use it to do tasks and provides the user with a conscious sensibility resulting in increased feelings of body-ownership towards the prosthesis (Graczyk, Gill, Tyler & Resnik, 2019). Another study indicates that artificial tactile and proprioceptive feedback improves the performance and confidence of amputees in object identification tasks (Schiefer, Graczyk, Sidik, Tan & Tyler, 2018).

1.1 Problem Identification

Prosthetic devices play a critical role in restoring ADL at the rehabilitation stage after the amputation of a diseased or damaged limb. These devices improve mobility of the patient and can improve the patient's ability to execute ADL (Trafton, 2017).

It is estimated that 20% of amputees reject their artificial limbs (Trafton, 2017). A systematic review, which studied the available literature from the past 25 years, found that approximately 1 in 5 people with an upper limb amputation reject their prosthesis which results in its non-use (Biddus & Chau, 2017). The extensive review suggests that this number is much higher than is published as the majority of studies were conducted via rehabilitation centres and; therefore, non-wearers that do not use these services may not have been accounted for in the study. According to another study, a significant amount of amputees forgo using the fancier prosthetic devices and opt rather for the simpler prostheses or none at all. The reason for this is the lack of sensory capability of the artificial limb, particularly in the realm of proprioception (Dudkiewicz et al., 2004). Of the prosthesis rejecters, 85% cited the reason for this rejection as the absence of proprioceptive feedback (Graczyk et al., 2019). It has been observed by Biddus & Chau (2017) that incorporating proprioception in a prosthetic device would greatly improve patient care and aid amputees in returning to normalcy.

One of the greatest limitations of current prosthetic devices is failing to provide the user with sensation. The absence of sensory feedback proves difficult for amputees in execution of ADLs with finesse. However, upper limb amputees who use prostheses often demonstrate better performance in ADL compared to amputees that do not use prostheses which highlights the importance of the development of a sensory feedback system which facilitates an enhancement in prosthesis use. Consistent collaboration between an amputee's occupational therapist (OT) and prosthetist is paramount to the success in the life of the amputee (NSW Agency for Clinical Innovation, 2019; Frederiks et al., 2013).

This project is aimed at developing a non-invasive system to work in conjunction with an existing body powered prosthesis to mediate detection of proximity and touch, and to mediate detection of the motion and position of the fingers of the prosthesis providing the user with both proprioceptive feedback and feedback to indicate touch and proximity.

1.2 Research Question, Hypothesis and Aim

The research question proposed for this study is whether a non-invasive sensory feedback system can work in conjunction with an existing body powered prosthesis that provides the user with improved tactile and proprioceptive perception?

This project aims to develop a non-invasive sensory feedback system, including proprioceptive feedback, to work in conjunction with an existing body powered prosthesis that provides the user with increased tactile and proprioceptive awareness demonstrated in the form of improved results in an object identification and size discrimination (OISD) test, improved results in confidence levels and improved results in response time (time taken to execute tasks).

The hypothesis proposed for the project is that adding artificial somatosensation (sensory feedback) improves object identification and size discrimination (OISD) accuracy when using a prosthesis, improves feelings of confidence and reduces response time in execution of tasks.

1.3 Objectives

The three primary objectives, with their secondary objectives, identified for the successful execution and completion of this project are:

1. To design and develop a non-invasive sensory feedback system for measuring proprioception, proximity and touch. This will be achieved by:
 - Designing/choosing the sensing mechanisms,
 - Designing/choosing non-invasive feedback mechanisms,
 - Designing the electronic circuitry, and
 - Ensuring its suitability with an existing body powered prosthesis and its manufacturability.

1.4. SYSTEM PARAMETERS IDENTIFICATION

2. To test and optimise the sensory feedback system by focusing on:
 - The sensing range of the sensing mechanisms,
 - The sensitivity and accuracy of the sensing mechanisms,
 - The intensity range of the feedback mechanisms,
 - The placement of the feedback mechanisms on the amputee,
 - The range of detectable materials, and
 - The reliability of the device.
3. To validate the sensory feedback system through a preliminary study conducted on able-bodied adult volunteers by:
 - Validating the sensing range of the device and the range of materials it can detect,
 - Validating the accuracy and sensitivity of the device in relaying feedback to the user about sensory and proprioceptive information, and
 - Obtaining results about the tactile and proprioceptive awareness the device provides to the user.

1.4 System Parameters Identification

System parameters are the variables that will influence the success of the sensory feedback system. The following variables have been identified as system parameters for this project:

- The weight of the sensory feedback system,
- The sensitivity and accuracy of the sensing mechanisms (and their ability to detect a wide variety of materials), and
- The placement of the feedback mechanisms on the user and the chosen method of feedback.

1.5 Project Scope and Limitations

This project is completed in partial fulfilment of the degree: Masters in Science in Biomedical Engineering (coursework and minor dissertation), as the minor dissertation portion of the author's degree (which makes up 90 credits of the total 180 credits).

The design and development of the body powered prosthesis used during testing is not in the scope of this project.

The scope of the project is limited to the design and development of a proof-of-concept of a non-invasive sensory feedback system and its subsequent design validation. The design validation of this system is conducted through bench testing of the device and through a preliminary study conducted on able-bodied, adult volunteers. A modified body powered prosthetic arm will be used during testing to simulate an environment of amputee use. This will be done by making use of a bypass socket designed and developed by Timm et al. (2019) which essentially extends the forearm and allows the user to secure their own hand within the socket (placing it out of the way during testing). This enables the prosthetic hand to act as an extension of the healthy arm.

1.6 Dissertation Overview

This dissertation documents the research and design processes followed in the completion of the project. Figure 1.1 presents the sequence of Chapters this document follows.

The dissertation begins with an introductory chapter presented above. The problem is identified and summarised briefly followed by a detailing of the aim, objectives, and scope and limitations of the project.

Chapter 2 consists of a detailed review of the literature specific to upper limb amputations and amputees. An analysis of the disease state is conducted followed by a review of existing solutions. Methods of evaluation are discussed.

The knowledge gathered in Chapter 2 is used in Chapter 3 to develop a design methodology whereby the system is described, its critical parameters are identified and its functional subsystems are designed and developed.

Chapter 4 begins with a Failure Modes and Effects Analysis (FMEA) of the device. A validation of the functional subsystems identified in Chapter 3 is conducted which flows into the pre-clinical validation of the system as a whole whereby bench testing and a preliminary study with able-bodied adult volunteer participants is conducted.

Chapter 5 presents the results and analysis of results from the testing described in Chapter 4. Finally, conclusions followed by recommendations and future work are discussed in Chapter 6 and 7, respectively.

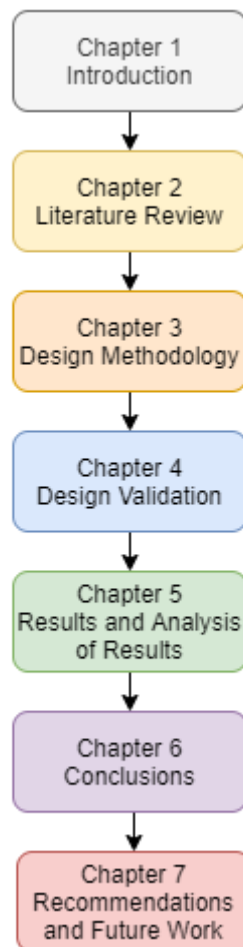


Figure 1.1: Overview of Dissertation.

Chapter 2

Literature Review

This chapter summarises the disease state analysis whereby key statistics and information pertaining to upper limb amputations and amputees are presented, and reviews studies conducted by other researchers who have contributed noteworthy information in the particular field of development of sensory feedback systems for upper limb prostheses.

2.1 Analysis of Disease State

2.1.1 Epidemiology

The absence of a limb can be categorised broadly into two categories:

1. Amputation: the removal of an entire limb or part thereof caused by disease, injury or surgery.
2. Congenital limb deficiency (CLD): the condition that results in an infant being born without an entire limb or part thereof.

In the United States (US), for every 100 000 live births 26 are born with CLD and the upper limb is involved 58.5% of the time (The Cape Amputee Clinic, 2014). Poor circulation (or vascular disease) is the cause of 54% of all amputations. Trauma accounts

for 45% of all amputations, and congenital limb deficiency and cancer cause less than 2% of all amputations. The upper limb is involved 68.6% of the time for trauma-related amputations and 23.9% of the time for cancer-related amputations (Amputee Solutions, 2012).

Approximately 2.1 million people are living with limb loss in the US. By 2050, this number is predicted to double (Access Prosthetics, 2017). It is estimated that, in the US alone, 185 000 amputations occur per year (approximately 500 per day) (Amputee Coalition, 2019). Amputations to the upper limb account for approximately one-third of all amputations globally (Access Prosthetics, 2017).

The data in Table 2.1 has been extrapolated to determine an approximate number of arm amputees in the South African context (approximately 262 300 people when taking the population of South Africa to be 57.7 million people). All values refer to the number of people.

Table 2.1

Global and South African Population Distribution of Amputees (Maurice LeBlanc, 2018).

| | |
|---|---------------|
| Global population | 7.7 billion |
| Incidence of amputation | 1.5 per 1000 |
| Global population of amputees | 11.55 million |
| Percentage of arm amputees in the world | 30 % |
| Arm amputees globally | 3.5 million |
| Arm amputees in developing countries | 2.8 million |
| Population of South Africa | 57.7 million |
| Estimated arm amputees in South Africa | 262 300 |

A study conducted at a Western Cape physical rehabilitation centre found that of the 30 volunteers in the study, most were male (20 people), the dominating age group was between the ages of 51 and 60 (14 people) and 25 were unemployed (indicating the amputation as the primary reason for unemployment). Of 30 volunteers, 26 received a monthly income between R 1001 and R 2000 (Pienaar, 2018). Another study by the University of the Western Cape concluded that most participants were male with an average mean age of amputation of 23 years (Western Cape, 2018). In 2013, 43.5% of the population of South Africa was living in rural areas (Rural Health, 2013). The

proportional of the total population of South Africa that identifies as black is 79.4%; therefore, it could be suggested that for the South African context the majority of amputees are black (World Population Review, 2019). The upper limb dominates traumatic amputations with males more likely to experience trauma-related amputations than females. Furthermore, traumatic amputations are most prevalent in the younger, active age groups (Jabeen & Sajjid, 2015).

In summary, from the information stated above, it is important to note that if a demographic of people were to be singled out in the South African context regarding upper limb amputations, the group would largely be made up of young, black, males who are mostly unemployed and therefore when designing with the South African context in mind, one needs to remember that the device would need at least to suit the basic needs of a demographic such as this (i.e. be cost effective, be suitable for rural settings etc.).

2.1.2 Physiological and Pathophysiological Overview

Proprioception is the ability of the body to sense stimuli associated with equilibrium, motion and position. It is the body's ability to know the force muscles are exerting during activities (Medicine Net, 2019).

Proprioception plays a critical role in aiding the interaction humans have with their environment and allows them to move consciously (Medicine Net, 2019). The receptors in the skin responsible for proprioception are the reason humans can close their eyes and lift their arm's above their head and know where it is in space. Sensory transduction is the process in which stimuli are received by the skin, transformed into electrochemical signals and sent to the brain to interpret. Figure 2.1 illustrates this process.

A receptor cell can be categorised according to its location in the body, its function or its cell type (Biga et al., 2018). In the paragraphs that follow, the sensory receptors have been described, according to their location relative to stimuli, and broken up into three groups: exteroceptors, interoceptors and proprioceptors.

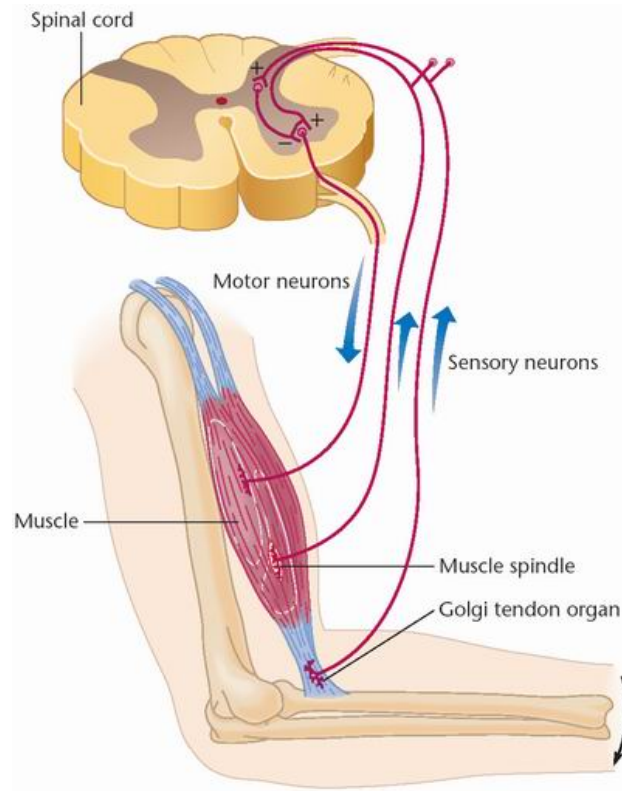


Figure 2.1: Sensory Transduction and Proprioceptors (MediaLook, 2017).

Exteroceptors detect stimuli from outside of the body by notifying the central nervous system (CNS) about the state of the environment. This category includes receptors for hearing, smell, cutaneous sensation and vision. The cutaneous receptors, found in the skin, provide the ability to sense pressure, touch, vibration, temperature, texture and pain (Biga et al., 2018). Conversely, interoceptors (or visceroreceptors) detect stimuli within the body and are associated with the autonomic nervous system. Their focus is on visceral information and includes receptors for blood (ph, pressure and volume). Interoceptors are directly engaged in maintaining homeostasis within the body through negative feedback (Biga et al., 2018).

Proprioceptors detect the position of tissue in the body as it moves and are; therefore, located close to moving parts of the body like tendons and muscles (Biga et al., 2018). Although there are many proprioceptors that interact with the brain via sensory neurons, there are three main receptors related to the musculoskeletal system namely: the muscle spindle, the golgi tendon organ and the Pacinian corpuscle (Core Walking, 2019). Table 2.2 lists the basic functions and location within the body of the three main proprioceptors. Table 2.3 has further classified and summarised five sensory receptors based on the type of stimulus they sense. Figure 2.2 presents some of these in image form.

Table 2.2

A Summary of the Three Main Proprioceptors in the Body (Core Walking, 2019; Biga et al., 2018).

| Proprioceptor | Function | Location in the Body |
|----------------------|---|---|
| Muscle spindle | Relays to the brain how much a given muscle can stretch (i.e. provides information about changes in muscle length) (stretch receptor) | In line with muscle fibres (Figure 2.1) |
| Golgi tendon organ | Relays to the brain to slow down when a muscle does not have the ability to stretch (i.e. provides information about changes in muscle tension) (stretch inhibitor) | In line with tendons (Figure 2.1) |
| Pacinian corpuscle | Pressure sensor in charge of detecting changes in movement and force within the body | Deep in the dermis of the skin (Figure 2.2) |

Table 2.3

Sensory Receptors found in the Skin (Categorised by Type of Stimulus Sensed) (Nature, 2019).

| Sensory Receptor | Stimulated by | Associated with |
|-------------------------|---|--|
| Chemoreceptor | Changes in the chemical concentration of substances | Taste, smell, blood pH |
| Nociceptor | Tissue damage | Pain |
| Thermoreceptor | Changes in temperature | Hot, cold, pain |
| Mechanoreceptor | Changes in pressure or movement (mechanical force) | Gravity, motion, body position, hearing, vibration, texture, touch |
| Photoreceptor | Light energy | Vision |

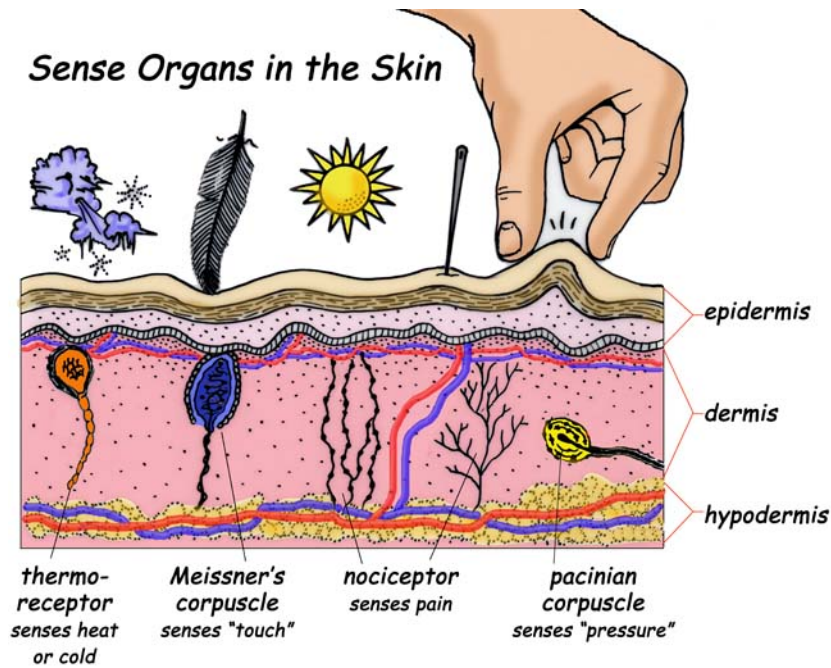


Figure 2.2: The Skin and its Sensory Receptors (Nature, 2019).

The precise control of movement of artificial limbs is restricted because of the lack of proprioceptive feedback (Treacy, 2018). Proprioceptive and sensory feedback is critical for the precise, fluid execution of movement of limbs. It plays a key role in the slow alteration of motor commands concerning changes in biomechanical properties of the limbs (Grey, 2010).

The important role that sensory feedback from the receptors in the arm or hand plays is two-fold: one is feedback for action and the other is feedback for perception. The first provides feedback for producing controlled movements of the hand or arm (i.e. proprioceptive feedback) and the second provides feedback that manifests itself as sensation (touch, pressure, temperature etc.) (Darbandi et al., 2011). These types of sensory feedback are not mutually exclusive. For example, to move our hands to manipulate and explore objects accurately and completely; one requires feedback in the form of sensation, too.

Thus, in order fully to provide sensory feedback; the process can be summarised as:

1. Stimuli are detected by artificial receptors (sensors),
2. A mean to transfer the sensed information to intact skin, and finally
3. A relearning and adaptation of the central nervous system (a type of Pavlovian conditioning) to new types of afferent signals must occur.

2.1.3 Overview of Amputations and Prosthetic Devices

Any amputation is a life-changing and distressing experience. Often, to help an amputee adjust to life and to improve performance in ADL; they will eventually be fitted with a prosthetic device. The type of prosthetic device an amputee is fitted with will largely depend on, but is not always limited to, the length of the residual limb. Figure 2.3 and Table 2.4 briefly illustrate and describe the types of upper arm amputations, respectively.

Broadly, prostheses can be categorised as either passive or active devices. Within these two categories, they can be further elaborated upon based on the type of energy input they require to operate. Table 2.5 presents a brief overview of the five main categories of upper limb prosthetic devices amputees may potentially consider.

Depending on the individual clinical and personal needs of each patient, there are many different factors to consider when it comes to choosing the right prosthetic device. One of the most critical factors is the cost of each technology, which varies drastically as the complexity of the device increases; with body powered prosthetic devices typically ranging between \$ 4 000 and \$ 10 000 and electrically powered or myoelectric prostheses ranging between \$ 25 000 to \$ 75 000 (Carey, Lura & Highsmith, 2015).

It is important to understand that wearing of a prosthesis does not necessarily relate to its use. Studies have shown that perceived usefulness scores for several daily living tasks are marked similarly for both body powered and myoelectric prosthetic devices; two devices in incredibly different price categories. Other studies indicate that body powered prostheses are considered adequate for ADL and just as functional as the more advanced and more expensive myoelectric devices (Wheaton, 2017). In terms of sensory feedback, body-powered prostheses are often considered a more attractive option because the cabling of the harness provides indirect sensory feedback to the user about the force exerted by the device (a type of proprioceptive feedback) (Schiefer et al., 2018).

AMPUTATION LEVELS

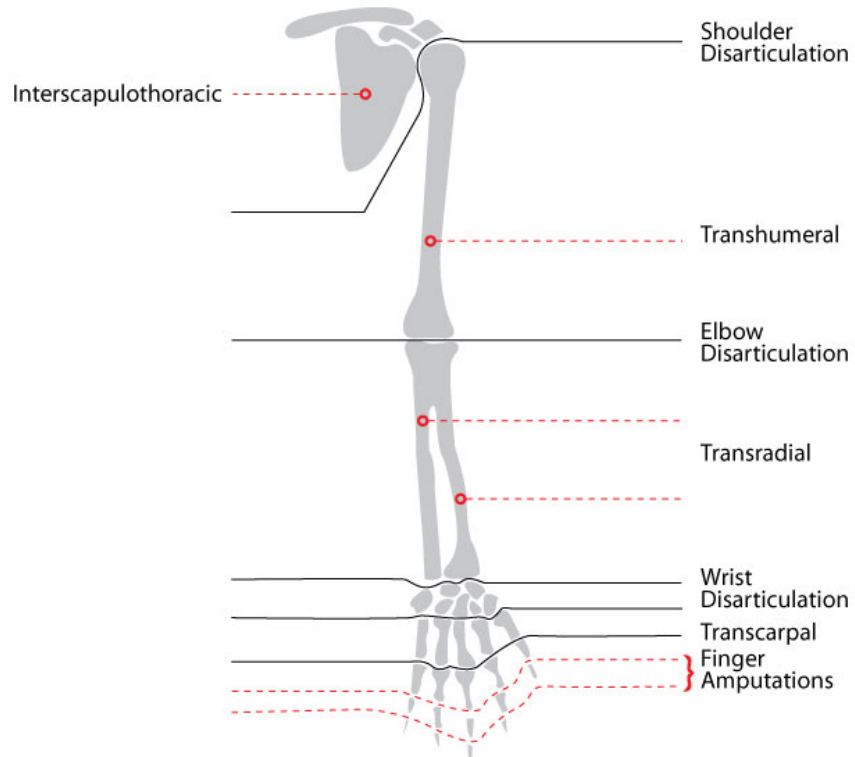


Figure 2.3: Types of Upper Limb Amputations (Du Plessis Orthotics & Prosthetics, 2021).

Table 2.4

Types of Upper Limb Amputations (Hanger Clinic, 2019)

| Location of Amputation | Amputation Term |
|--------------------------------------|--------------------------------|
| Finger or partial hand | Transphalangeal or transcarpal |
| Through the wrist joint | Wrist disarticulation |
| Below-elbow | Transradial |
| Through the elbow joint | Elbow disarticulation |
| Above-elbow | Transhumeral |
| Through the shoulder joint | Shoulder disarticulation |
| Entire shoulder girdle (forequarter) | Interscapular thoracic |

Table 2.5

Summary of the Categories of Upper Limb Prosthetic Devices.

\$ indicates up to \$ 4000 , \$\$ can range between \$ 4000 to \$ 10 000, \$\$\$ can range between \$ 25 000 to \$ 75 000.

| | Category of Prosthetic Device | Description | Functionality | Power Source | Relative Price |
|---|--------------------------------------|---|----------------------|---------------------|-----------------------|
| 1 | None | The person choses to forgo utilisation of a prosthetic limb altogether. | - | - | - |
| 2 | Passive | These devices can be static (i.e. cannot move at all and therefore, are purely cosmetic) or adjustable (feature an adjustable mechanism/parts of the prosthesis can be changed to multiple orientations by that of the functional hand or by pushing the prosthesis against the surroundings in the environment) (Maat et al., 2018). | Low | None | \$ |

Table 2.5

Summary of the Categories of Upper Limb Prosthetic Devices.

\$ indicates up to \$ 4000 , \$\$ can range between \$ 4000 to \$ 10 000, \$\$\$ can range between \$ 25 000 to \$ 75 000.

| Category of Prosthetic Device | Description | Functionality | Power Source | Relative Price |
|--------------------------------------|---|----------------------|---------------------|-----------------------|
| 3 Body Powered | Commonly known as cable-driven prostheses, these devices rely on a system of cables or harnesses and the gross motor movements of the user to control the prosthesis. Typically, the user will use the movements of the chest, shoulder and/or elbow to assist in the control of the device. Thus, these devices rely on the user to generate enough force to operate efficiently but also rely on a large enough functional work envelope to enable the user to perform tasks effectively (Zenie, 2013). | Medium | Internal (User) | \$\$ |

Table 2.5

Summary of the Categories of Upper Limb Prosthetic Devices.

\$ indicates up to \$ 4000 , \$\$ can range between \$ 4000 to \$ 10 000, \$\$\$ can range between \$ 25 000 to \$ 75 000.

| Category of Prosthetic Device | Description | Functionality | Power Source | Relative Price |
|---------------------------------------|--|---------------|--------------|----------------|
| 4 Electrically Powered or Myoelectric | <p>Electrically powered prosthetic devices use electric motors to actuate prosthetic hands. Unlike body powered devices, actuation of these devices occurs with relative ease, not requiring a large functional work envelope.</p> <p>Control of these devices is often achieved through the use of electromyographic (EMG) sensors which sense muscle activity and communicate that to the motors (Zenie, 2013). With increased functionality and control of the device comes increased complexity in the design and development which ultimately leads to an increased cost relative to the simpler devices.</p> | High | External | \$\$\$ |

Table 2.5

Summary of the Categories of Upper Limb Prosthetic Devices.

\$ indicates up to \$ 4000 , \$\$ can range between \$ 4000 to \$ 10 000, \$\$\$ can range between \$ 25 000 to \$ 75 000.

| Category of Prosthetic Device | Description | Functionality | Power Source | Relative Price |
|--------------------------------------|--|----------------------|---------------------|-----------------------|
| 5 Hybrid | Combination of a body powered system and an electrically powered system which typically include a body powered elbow and a myoelectric terminal device (such as a hook or a hand). It enables both components to be operated simultaneously and allows for increased force of the hand for gripping (Zenie, 2013). | Medium - High | Combination | \$\$ - \$\$\$ |

2.1.4 Sensory Substitution

Sensory substitution is a method whereby the use of one sensory modality is used to assist or replace lost somatosensory input (Schiefer et al., 2018). It has shown particular promise in the context of amputation and compensation for sensory loss (Guemann et al., 2019; Alva et al., 2020). Table 2.6 presents some of the methods that can be used in the substitution of senses.

Table 2.6
A Summary of Some of the Methods of Sensory Substitution.

| Feedback Method | Approach | Mechanism of Action | Additional Comments |
|--|----------|--|---|
| Targeted reinnervation | Invasive | Nerves that once innervated a severed limb are redirected to a proximal muscle and to skin sites on the residual limb and so sensory afferent signals of the redirected nerves will reinnervate the skin of the transfer area (Marasco, Schultz Kuiken, 2009). | This is an invasive technique which would require surgery and is considered out of the scope of this project. |
| Central nervous system (CNS) electrode | Invasive | Similar to peripheral nervous system electrode implantation, except that it focuses on brain-computer interfacing whereby the electrode is implanted directly into the central nervous system. This technique is only suitable for patients without available peripheral nerves but carries even greater risk than PNS electrode implantation (Antfolk, 2013). | This is an invasive technique which would require surgery and is considered out of the scope of this project. |

| | | | |
|---|--------------|--|---|
| Peripheral nervous system (PNS) electrode | Invasive | Neural electrodes are invasively (surgically) implanted in the peripheral nervous system. Studies indicated the goal of this technique has technological limitations with respect to neural interfaces and poor knowledge of how the hand encodes stimuli and sends them to brain. It is suggested that the electrodes do not last long due to cellular foreign-body response and therefore evidence suggests risks do not outweigh the benefits as of yet (Antfolk, 2013). | This is an invasive technique which would require surgery and is considered out of the scope of this project. |
| Temperature | Non-Invasive | Temperature communicates to users information about their surroundings and potential dangers that involve heat (or in severe cases: cold). Production of heat on the upper arm to correspond with temperature senses at the prosthetic hand is the only recording of temperature feedback found in literature (Stephens-Fripp et al., 2018). Most studies make use of Peltier elements, which are lightweight and responsive at changing their temperature, but can also be quite power inefficient when used incorrectly (Antfolk, 2013). | Literature suggests that this method of feedback be used simultaneously with another method of feedback but not solely by itself until further advancements are made as it has not yet been explored in great detail. |

| | | | |
|-------------------|--------------|--|--|
| Audio | Non-Invasive | <p>Studies have shown positive results in using varying frequency to correspond with object location as well as varying the volume or timbre of auditory signals to represent the level of grasping force (Gibson Artemiadis, 2014). One study used different sounds (the sound of a cello to correspond the force on the thumb and piano for the index finger) to communicate movements and forces of a robotic hand. This showed that it is possible to use auditory feedback to convey artificial proprioceptive and exteroceptive information (Gonzalez et al., 2012).</p> | <p>All studies recorded in the literature were conducted in a laboratory with minimal background noise and with the use of headphones and therefore, further investigation into the efficacy of this method and its suitability in the real-world context is required.</p> |
| Augmented reality | Non-Invasive | <p>The use of augmented reality, like the use of Google glasses, has been explored to communicate grasping force, aperture angle, contact time etc. of a prosthetic hand to its user with positive results in task performance when moving objects using variable strengths without breaking the objects (Markovic et al., 2017).</p> | <p>Studies indicate that although performance repeatability may improve and increase with this method, the cognitive efforts required to use this method also increase.</p> |

| | | | |
|--------------------------|--------------|---|--|
| Mechanotactile pressure | Non-Invasive | <p>Mechanotactile pressure is achieved when the user receives feedback in the form of a pusher applied to the skin applied at a normal force (Antfolk, 2013). Typical mechanisms of action include either the use of skin stretch (a rocker on the bicep, or rotational part that resembles a windshield wiper), pressure or contact pads, actuators or mechanically winding belt (Stephens-Fripp et al., 2018).</p> | <p>Studies indicate good results from the various methods when using mechanotactile pressure to relay sensory information to the user; however, the focus of the studies was centered around myoelectrically controlled prosthetic devices and therefore the results were focused on indicating to the user information such as hardness of objects or grip strength and pressure.</p> |
| Phantom limb stimulation | Non-Invasive | <p>Other than phantom limb pain that amputees experience, amputees can also have locations that are known as phantom limb digits which, when touched, can trigger sensations that tell the brain their missing finger is being touched. This provides a pathway for a much more natural and efficient means of communication for a range of sensations that would not require training (Stephens-Fripp et al., 2018).</p> | <p>Although some studies indicate positive results, it is important to note that phantom digit locations are different for every amputee. The size and location can vary drastically amongst individuals which would make design and development of an optimum device difficult and a large degree of customisation would be required.</p> |

| | | | |
|-----------------------|---------------------|--|---|
| <p>Electrotactile</p> | <p>Non-Invasive</p> | <p>Electrotactile stimulation is focused on applying small currents to the surface of the skin of the user of the prosthetic device through small, lightweight electrodes (Rossi et al., 2018). Benefits include no moving parts and efficient power consumption and most importantly, intensity, pulse width, frequency and location of the stimulation (with multiple electrodes) can all be and reliably controlled with this form of feedback.</p> | <p>According to Rossi et al., although this feedback mechanism is low cost, light weight and compact, it has been shown to produce a range of unpleasant sensations for the user, and its performance, relative to that of vibrotactile feedback, has been shown to be less effective (2018).</p> |
|-----------------------|---------------------|--|---|

| | | | |
|--------------|--------------|--|--|
| Vibrotactile | Non-Invasive | <p>Vibrational feedback typically uses small, lightweight, commercially available vibrators (vibrating motor discs) which are applied to the surface of the skin and target the Pacinian corpuscle (Stephens-Fripp et al., 2018). The user will learn to associate a vibration at the site with one of the senses associated with the prosthetic hand. Some of the disadvantages of this method include: a time delay for generating the vibration, a limited bandwidth, perception of vibrational frequency has been reported to be affected depending on how tightly it is attached to the user (Stephens-Fripp et al., 2018; Antfolk, 2013). Like electrotactile feedback, vibrotactile feedback makes use of motor discs which contain no moving parts and allow for a high level of control with respect to: intensity, pulse width, frequency and location of the stimulation.</p> | <p>Studies indicate that in some subjects there is a reduction in cognitive effort when vibrotactile feedback was introduced as a feedback method (Stephens-Fripp et al., 2018). Other studies have indicated that vibrotactile feedback improves embodiment in amputee subjects (Antfolk, 2013). However, unlike phantom limb stimulation, with vibrotactile as a feedback method, the user will be required to undergo training to develop the full benefit of the device.</p> |
|--------------|--------------|--|--|

2.2 Modified Body Powered Prosthesis Overview

The design, development and preliminary testing of the modified body powered prosthesis, named ADL arm, forms part of a separate masters project; one which is not linked to this one. The author of this thesis claims no ownership of the design and works conducted by Timm et al. (2019), the inventors of ADL arm, in the development of the prosthetic device. The modified body powered prosthesis is used solely for the purposes of conducting the preliminary testing of the sensory feedback system proposed in this thesis.

For the purposes of the preliminary study, able-bodied individuals will be used for voluntary participation in the study. Therefore, to facilitate an environment that simulates amputee use, a bypass socket, designed and developed by Timm et al. (2019), is used as presented in Figure 2.4. The socket essentially extends the forearm which allows the user to secure their own hand within the socket (placing it out of the way during testing) and enables the prosthetic hand to act as an extension of the healthy arm.



Figure 2.4: ADL arm Designed, Developed and Preliminarily Tested by Lara Timm (Timm et al., 2019) .

The prosthetic device designed, developed and preliminarily tested by Timm et al. (2019) and presented in Figure 2.4 can achieve the following grasp shapes: medium wrap, lateral, adducted thumb and index finger extension. From preliminary testing, results indicate the device is able to achieve 17 of the 28 set-out ADL successfully without any frustration or discomfort and with relative ease (Timm et al., 2019). It is a voluntary-closing (VC) device which means it requires effort to close the prosthesis. The advantage associated with VC devices is that the user is provided with tension feedback that enables them

to feel, to an extent, the amount of force applied to the object (Timm et al., 2019). It must be emphasised that this is the first prototype of the body powered prosthesis. It has been objectively tested by the inventor only, and human participant testing must still be conducted to validate its design.

2.3 Existing Sensory Feedback System Solutions

Over the last 50 years, there have been massive technological advancements in the realm of prosthetic limb design and still while futuristic devices are being developed, amputees do not frequently make use of them due to high costs associated with the devices as well as the fiscal policies of coverage and reimbursement associated with the technologies (Wheaton, 2017).

The restoration of sensation to the prosthetic limb remains an even greater problem - one that if solved could change how prostheses are integrated in an amputee's self-image and could help to alleviate the abandonment rate associated with prosthesis use.

There is currently no proprioceptive or sensory feedback system for upper limb prostheses available on any commercial market. However, there are a number of universities across the globe exploring the topic for the purpose of academic studies. A summary of some of the workings of academic devices is presented in Table 2.7.

Table 2.7
Summary of Some of the Existing Solutions.

| Name | Sensing Mechanism | Feedback Mechanism | Reference |
|---------------------|--------------------------------|---|---------------------|
| HapPro | Electromyography (EMG) sensors | Synergy-based (a moveable contact on surface of the skin & haptics) | Rossi et al., 2018 |
| Skin-Stretch | Force sensors | Synergy-based (a moveable contact on surface of the skin) | McNaughton, 2014 |
| Stretch-Pro | Force sensors | Synergy-based (a moveable contact on surface of the skin) | Grioli et al., 2019 |
| E-Dermis | Pressure and touch sensors | Trans-cutaneous electrical nerve stimulation | Zhang, 2018 |

2.4 Methods of Evaluation

2.4.1 Object Identification and Size Discrimination (OISD) Test

To determine the impact sensory feedback has on prosthesis function, functional tasks that focus on integration with/depend on this type of feedback must be identified and performed with the prosthetic device. It must be emphasised that there are no standardised functional tests specific to upper limb prostheses to assess the impact of sensory feedback. However, in the human hand; object identification and discrimination tasks have been used to measure sensory capability performance and hand function in people with carpal tunnel syndrome, people who have had nerve surgery and those with neuropathy (Schiefer et al., 2018).

In these tasks, people are instructed to determine the object shape, size or texture. Objects differing in size or texture can be distinguished by visual inspection only, but objects that differ in compliance require tactile feedback during object deformation. Objects differing in size or shape require information about the hand position (i.e. proprioceptive feedback) paired with tactile feedback during object manipulation. An OISD test can be used to demonstrate the interpretation efficacy of sensory information (Schiefer et al., 2018).

For the purposes of this study, an OISD test will be designed and developed to test the efficacy of the sensory feedback system in how well it relays sensory information to the user and how well the user interprets the feedback. This is further explored and detailed in Chapter 4 Section 4.4.

Chapter 3

Design Methodology

This chapter outlines the design methodology of a sensory feedback system that mediates detection of the position and motion of the fingers of a body powered prosthesis, and mediates detection of touch and proximity of the prosthesis to objects.

3.1 Systems Overview and Design Process

Figure 3.1 presents a systems overview of the sensory feedback system whereby the device is separated into its two functional subsystems namely: the embodiment of the system (how it looks) and its sensory system (the electronic system). The sensory system can be further divided into its system components namely: the feedback mechanism, power supply, microcontroller and sensing mechanisms. The design process followed is presented in Figure 3.2. The design process began by conducting extensive background research which includes a detailed literature review as presented in Chapter 2 and obtaining input from an occupational therapist, Mr Michael Awood.

Using an extensive background research, system parameters of the project were identified as summarised in Section 1.4. The remainder of the design process was split among three sections of design based on the two functional subsystems stated above and lastly, a section for integrative system design whereby the two functional subsystems were connected. The integrated system was then taken forward into the design validation process.

3.1. SYSTEMS OVERVIEW AND DESIGN PROCESS

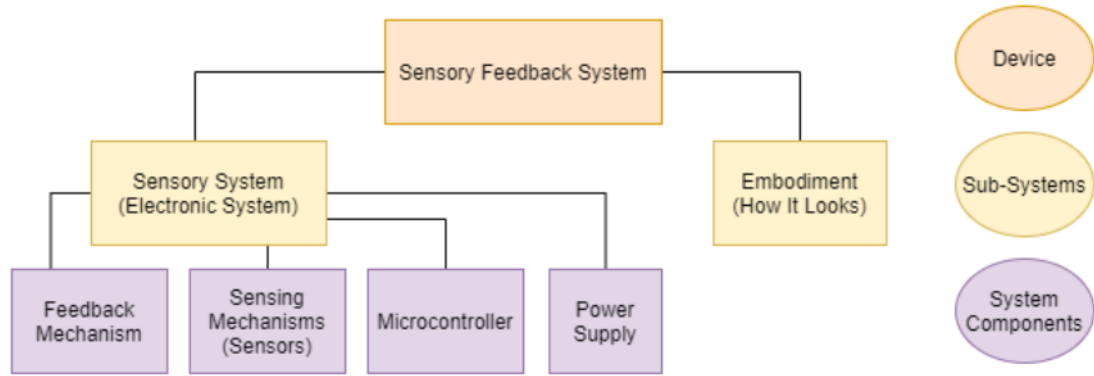


Figure 3.1: Systems Overview of the Sensory Feedback System.

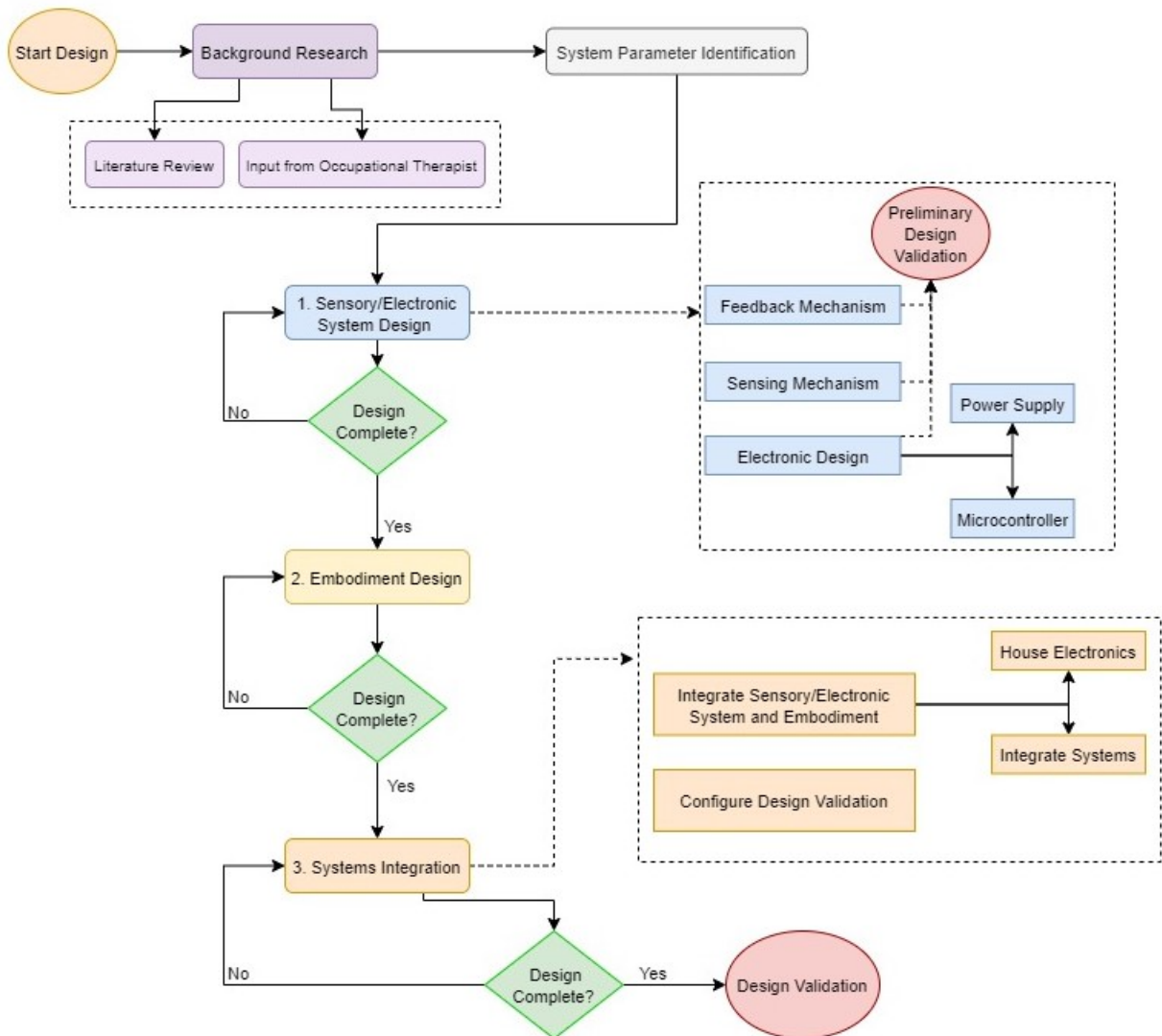


Figure 3.2: Design Process Followed.

3.2 Design of Functional Subsystems

3.2.1 Design Considerations and Requirements

3.2.1.1 Sensing Mechanism

This sensory feedback system is focused on providing feedback to the user about information pertaining to touch, proximity to objects and the position and motion of the fingers.

The following key requirements for the sensory component of the device have been identified:

- The chosen sensor/s must be able to detect a range of materials.
- The chosen sensor/s must be able to detect when the hand is in close proximity to an object (approximately within 4 cm) and when it is in contact with an object.
- The chosen sensor/s must be able to detect a range of positions of the fingers (from fully extended to fully bent; i.e. detect the angle between the palm of the hand and the fingers that ranges between 180° and 90° as this is the range of motion of the fingers of the prosthetic hand).

3.2.1.2 Feedback Mechanism

From Table 2.6, vibrotactile stimulation presents as the most promising method of sensory substitution and will be explored further in the design of this system.

A study conducted by Guemann et al. (2020), where the effect of vibration characteristics and arrangement on the tactile perception of the upper arm in healthy participants and upper limb amputees was investigated, showed that a circular arrangement elicits better results in terms of spatial discrimination and tactile intensity perception. Arrangements of vibration motors spaced equidistant, instead of a fixed 3 cm apart, elicit better results in terms of tactile discrimination. It is important to realise that the proportional spacings were always larger than 3 cm being either 4.7 cm or 4.1 cm depending on the arrangement (Guemann et al., 2020). Figure 3.3 illustrates the different vibrational arrangements that the study examined where circular proportional (A in the Figure) was seen to have the best results.

3.2. DESIGN OF FUNCTIONAL SUBSYSTEMS

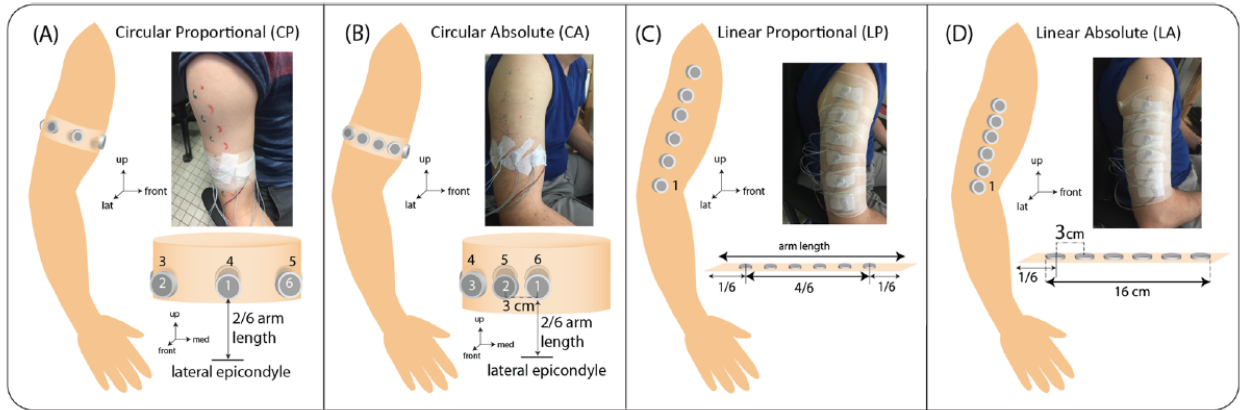


Figure 3.3: Different Vibrational Arrangements Examined in the Study by Guemann et al. (2020).

The vibrotactile feedback mechanism needed to meet the following requirements:

- The feedback system is to have a proportional circular arrangement.
- The feedback system is to have variation in intensity capabilities.
- The feedback system is to provide the user with increased tactile and proprioceptive awareness demonstrated by improved results in an object identification and size discrimination (OISD) test, improved results in confidence levels and improved response times.

3.2.1.3 Power Supply

The sensory feedback system is designed to be used in the awake hours of a person's day and to be recharged within their sleep cycle. According to a survey by the global app Sleep Cycle where the app mined data from more than 5000 South Africans, South Africans are the earliest risers and the earliest to bed globally. The survey suggests that 30% of South Africans receive approximately 7 hours of sleep a night; thus, on average South Africans are awake 17 hours of the day (Sleep Cycle, 2020). These values are averages and; therefore, for a factor of safety, it is decided to work with sleeping cycles of 6 hours (and awake cycles of 18 hours).

The following requirements are identified for the power supply:

- The size and weight of the power supply must be minimised for integration with the system such that no significant weight or volume is added to the prototype.
- The power source must be rechargeable within 6 hours (within a user's proposed sleeping cycle).
- The power source must be able to supply power to the system for at least 18 hours (the period of time for which the user would be awake).
- The power source must be mobile and easy to integrate within the system.

3.2.1.4 Microcontroller Selection

The microcontroller is responsible for controlling the actions of the sensory feedback system. The final prototype of the sensory feedback system requires a microcontroller suitable to provide the computing power necessary to control the system. It will receive input variation from the sensors and instruct the vibration motor discs on specific actions.

The chosen microcontroller must have the following criteria:

- A suitable number of inputs and outputs of which both digital and analogue types must be available (at least one analogue and at least four digital).
- A suitable number of timer peripherals must be accessible (at least three timers).
- The size and weight of the microcontroller must be minimised for integration with the system such that no significant weight or volume is added to the prototype.

3.2.1.5 Embodiment of System

Prosthetic limbs are generally designed to be lighter than the anatomical limbs they replace. More energy is required to use a prosthetic device because an amputee must compensate for the loss of bone, tissue and muscle of the amputated limb. The sensory feedback device must; thus, be as light as possible to reduce the overall energy exertion required by the amputee. According to the London School of Hygiene and Tropical Medicine, the average South African weighs 65.66 kilograms (LSHTM, 2012). According to Bernstein's investigation, the average percentage of the forearm and hand of total body mass for living subjects is 4.9% (Drillis, Contini & Bluestein, 1964).

3.2. DESIGN OF FUNCTIONAL SUBSYSTEMS

According to a publication where the authors developed a paediatric robotic thumb exoskeleton for at-home rehabilitation, it was determined that for the device to be considered lightweight; the weight of the device had to be less than 40% of the combined weight of a seven year old child's hand, forearm and upper arm. This value was set to 450 grams (Aubin, Sallum, Walsh & Stirling, 2013). When considering only the hand and forearm of the child (removing the upper arm), this value can be approximated to 300 grams.

According to Drillis, Contini & Bluestein (1964), the average weight of the human forearm and hand for someone that weighs 65.66 kilograms can be calculated as follows:

$$\frac{\textit{Segment mass}}{\textit{Total body mass}} = 0.049 = \frac{\textit{Forearm and hand mass}}{65.66} \quad (3.1)$$

$$\text{Forearm and hand mass} = 3.22 \text{ kg}$$

$$40\% \text{ of } 3.22 \text{ kg} = 1.29 \text{ kg}$$

From Equation 3.1, 40% of the weight of an average adult South African's forearm and hand is 1.29 kilograms. Therefore, the weight limit of the embodiment of the system can be given two limits: one soft limit and one hard limit. The harder limit being that the device cannot weigh more than 1.29 kilograms (the weight of the forearm and hand of an adult) and if the device were to be over this hard limit, this would be deemed unacceptable. A softer weight limit of 300 grams (the weight of the forearm and hand of a seven year old child) is deemed appropriate but since this was calculated with paediatric information, the device would not be deemed unacceptable if it were to weigh slightly more than this amount. The soft weight limit is an excellent design weight goal to work towards.

The key requirements and considerations for the embodiment of the system are as follows:

- The size and weight of the embodiment of the system must be minimised for integration of the entire system with the prosthetic device such that no significant weight or volume is added to the prosthetic device (hard limit of under 1.29 kilograms, soft limit of under 300 grams).
- The embodiment of the system must not hinder or restrict normal operation or function of the prosthetic device (i.e. it must still be able to operate and move as intended with the sensory feedback system attached).

3.3 Design Outcomes and Specifications

3.3.1 Sensing Mechanism: Touch and Proximity

3.3.1.1 Overview of Capacitive Sensors

Arduino is equipped with a Capacitive Sensing Library. This library allows two digital pins to be turned into a capacitive sensor (with one send pin and one receive pin). The only set-up required is a medium to high value resistor (ranging between 1 M Ω to 40 M Ω) connected between the pins and a piece of metal tape (in this case, copper tape) or foil on the end of a wire attached to one end of the resistor (Badger, 2008). This is a more frugal alternative to buying expensive sensors or designing a complex oscillating circuit which is typically required when designing capacitive sensors.

The Capacitive Sensing Library works as follows: when the send pin changes state; it will in turn eventually change the state of the receive pin. The time delay between the change in the send pin and the receive pin is determined by what is known as the RC time constant, τ (Badger, 2008).

$$\tau = R \times C \tag{3.2}$$

In Equation 3.2, R is the value of the resistor between the send and receive pins, and C is the capacitance at the receive pin (plus any other interacting capacitance such as human skin, this would be any object that would interact with the electric field of the capacitive sensor). From Equation 3.2, increasing the resistance will cause an increase in the time constant. Increasing the time constant leads to an increase in the sensitivity of the sensor (i.e. an increased resistance results in the sensor being able to sense changes in its electric field from further away) (Badger, 2008). The advantage capacitive sensors have over force sensitive resistors (FSRs) is their ability to sense both touch and proximity as opposed to FSRs which work in a binary way: either detecting force (triggering a 1) or not (triggering a 0) and therefore could only be used as a touch sensor.

Capacitance, measured in Farads (F), is a capacitor's ability to store electrical charge. The most prevalent type of capacitor is the parallel plate capacitor presented in Figure 3.4.

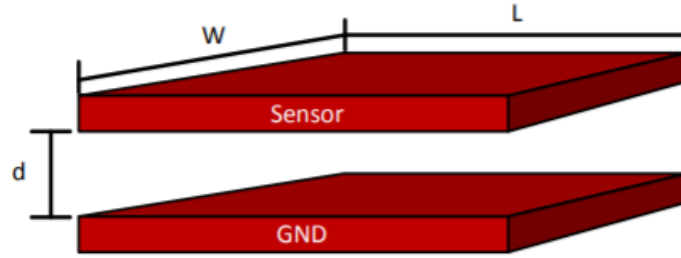


Figure 3.4: Parallel Plate Capacitor (SparkFun, 2021).

Capacitance of a parallel plate capacitor can be calculated as follows:

$$C = \frac{\epsilon_r \times \epsilon_0 \times A}{d} \quad (3.3)$$

From Equation 3.3: d is the separation between the two plates (measured in meters), A is the area of the two plates (measured in meters), ϵ_r is the dielectric constant of the material present between the plates and ϵ_0 is the permittivity of free space/air (8.85×10^{12} F/m).

From the equation, it is evident that all values in the numerator are directly proportional to capacitance (i.e. if either the material present between the plates is changed to one with a higher dielectric constant or the area of the plates is increased; capacitance, too, will increase). The separation between the two plates is inversely proportional to capacitance (i.e. to increase capacitance, the value of d must decrease meaning the distance between the two plates must shorten).

Figure 3.5 illustrates the movement of electric field lines in a parallel plate capacitor. The lines move from the higher voltage potential charged plate to the lower voltage potential charged plate. As shown in the figure, fringing occurs towards the ends of the plates. The affects of the fringing effect on the accuracy of readings varies (Texas Instruments, 2014). It is the increase in the capacitance as an object or hand moves closer that leads to the triggering of a capacitive sensor. When an object moves close enough, it cuts through the electric field lines produced by the capacitive sensor (Texas Instruments, 2014).

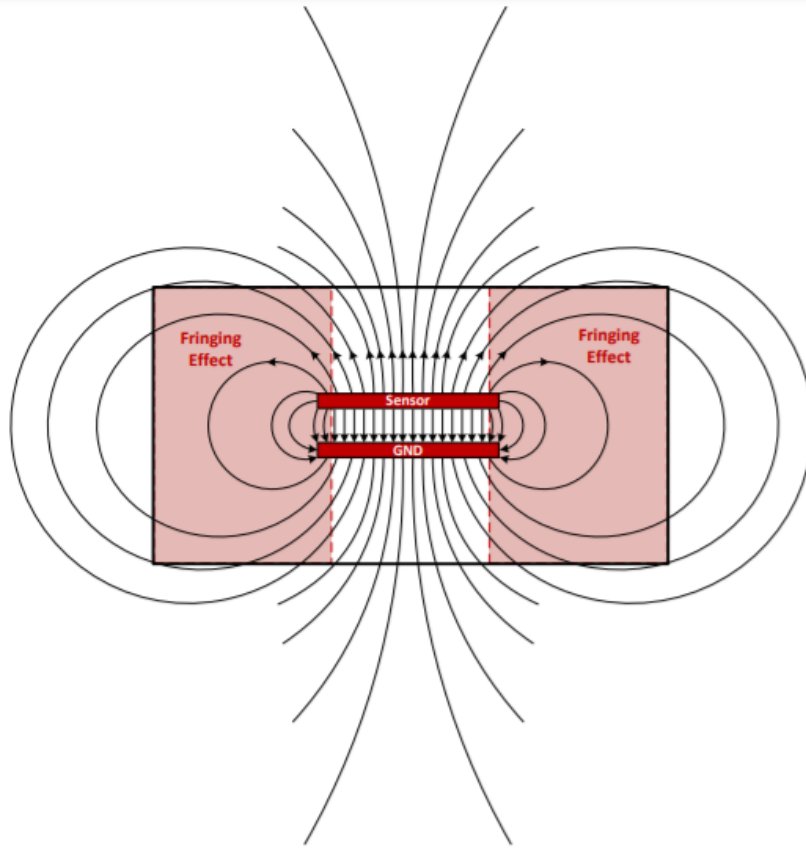


Figure 3.5: Electric Field of a Parallel Plate Capacitor (Texas Instruments, 2014).

3.3.1.2 Custom Capacitive Sensors

Custom capacitive sensors, made with copper tape, are used as dual-acting tactile and proximity sensors due to their high spatial resolution, their sensitivity to a range of materials and their ease of integration with other electronic systems. Figure 3.6 presents an image of various custom capacitive sensors. These sensors are not parallel plate capacitors but would instead be known as co-planar capacitors as the plates are not parallel to each other but rather in the same plane (the one plate is seen in the figure below and the second plate is the one which is connected to the receive pin of the Arduino). The principle and workings of co-planar sensors and parallel plate sensors remains the same.

Capacitive sensors with larger dimensions are able to detect objects from farther away due to their larger electric fields, but when writing code for the sensors, they can be calibrated to detect objects from a specified distance away. The final dimensions for the capacitive sensors were not finalised at this stage as the embodiment of the system had not yet been finalised. The final dimensions of the sensors and the chosen embodiment were decided in parallel and are further discussed in Section 3.3.5.



Figure 3.6: Image of Custom Capacitive Sensors Made with Copper Tape. Bottom Left: Sensor Without Embedding, Far Right: Sensor Embedded in 3D Printed Material, Top Left: Sensor Embedded in Silicone.

3.3.2 Sensing Mechanism: Position and Motion

A flex sensor (FSL0095103ST from SparkFun) was used to determine the position and motion of the fingers of the prosthesis. The datasheet detailing its specifications and information can be found in Appendix A.1. A single sensor is used and placed on the anterior surface of the middle finger to account for all the fingers. Unlike myoelectric prostheses, body powered prosthetic fingers do not move independently of one another. Instead, once the elbow is flexed or extended, the fingers move almost in sync and therefore, the use of one sensor on one finger to indicate the position and motion of all the fingers is deemed sufficient for the application.

A flex sensor is a variable resistor and measures the amount of deflection or bending. As the sensor bends (or flexes), the terminal resistance increases linearly. The flex sensor terminal is connected to an analogue pin on the Arduino Mini Pro. As the sensor changes bent angle, the voltage will change on the analogue pin. This voltage parameter can then be used to calculate an angle parameter (position). If one adds a time component to this; motion (how quickly it is changing angle) can be calculated as well. These parameters can be connected to vibration motors and the intensity of these motors can be used to indicate not only the position of the object on which the flex sensor is placed but the motion of the object as well.

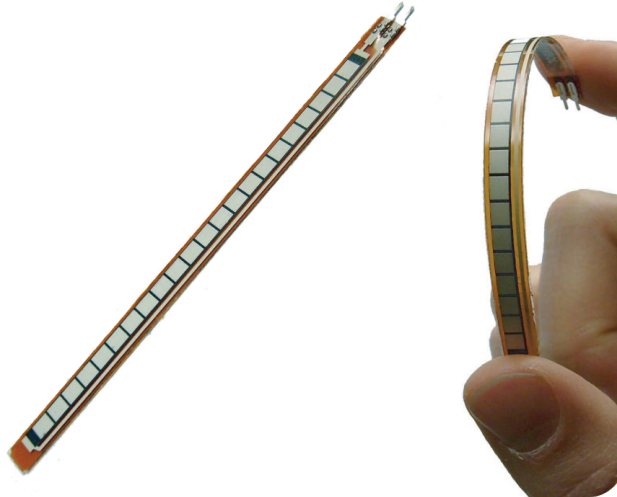


Figure 3.7: Flex Sensor Used to Determine Position and Motion of the Fingers of the Prosthesis (SpectraSymbol, 2014).

3.3.2.1 Microcontroller

An Arduino Pro Mini is used to generate the control signals of the waveforms for the vibration patterns in the final prototype. Its datasheet can be found in Appendix A.2. Figure 3.8 presents an image of the board and Figure 3.9 presents a pin diagram illustration.

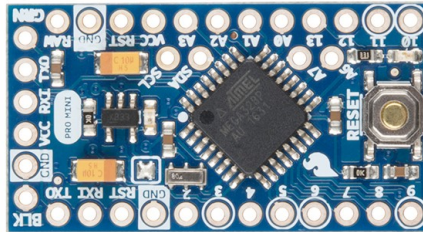


Figure 3.8: An Arduino Pro Mini 328 3.3V/8MHz (SparkFun, 2021).

Like its larger counterparts, the Arduino Pro Mini is powered by an ATmega328P microchip. It is a high performance, low power consumption, 8-bit microcontroller. Further advantages include that it is lightweight (2 g), compact in size (33 x 18 mm), much cheaper than other Arduino boards, has multiple digital input/output pins (14 in total of which 6 can be used as Pulse Width Modulation (PWM) outputs), has multiple analogue inputs (6 in total), has an on-board resonator) and three available timers.

The version of the board chosen for the final prototype is the 3.3 V 8 MHz board. Chosen as this version of the board uses less power and therefore has better power consumption. Furthermore, an 8 MHz clock speed is deemed sufficient for the application.

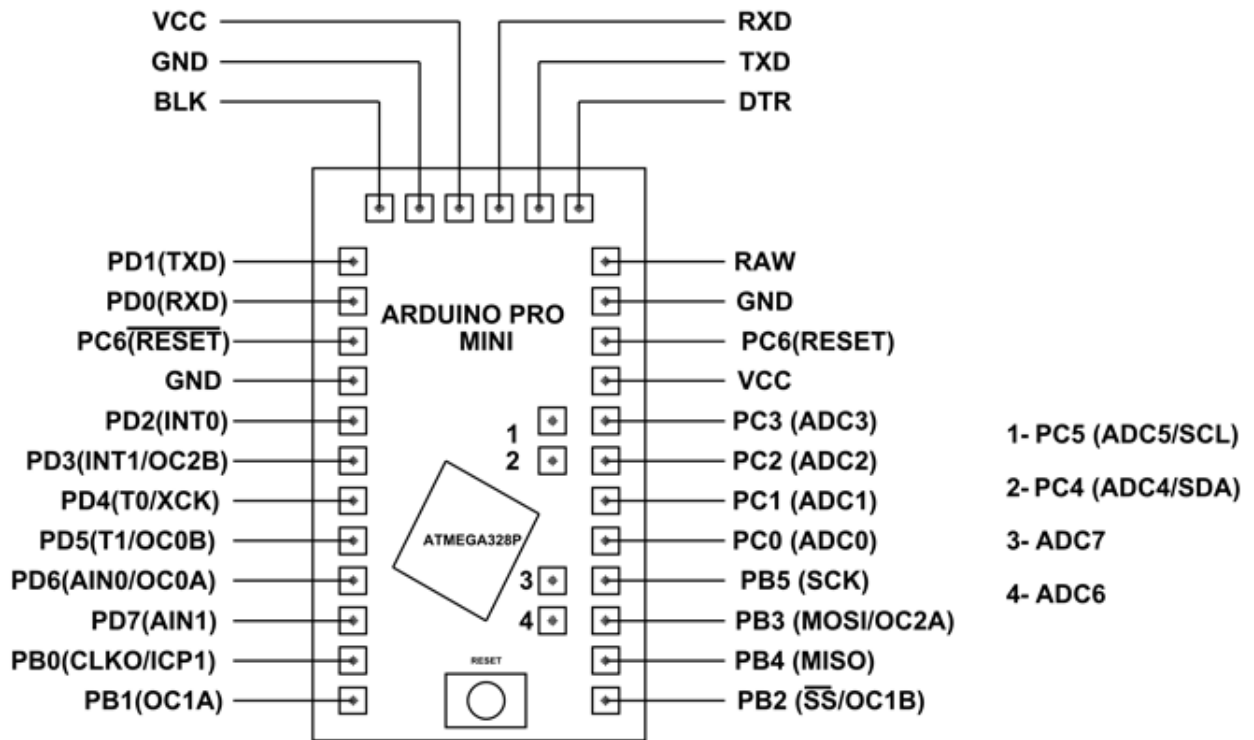


Figure 3.9: An Arduino Pro Mini Pin Diagram (Components 101, 2020).

3.3.2.2 Power Supply

A 3.7 V Lithium-Polymer (Li-Poly) 2500 mAh battery was used during rapid prototyping. A battery of capacity 2500 mAh can deliver 2500 mA to a system in one hour. Therefore, for a minimum of 18 hours; the sensory feedback system must operate on average over the 18 hours at 138.8 mA. To determine the suitability of the battery, a calculation of the power consumption of the device must be conducted.

Table 3.1 presents the power consumption of each component of the sensory feedback system. In an idle state, the Arduino Pro Mini, the capacitive sensors and the flex sensor are the only components which consume power from the battery (at 9.6 mA). The microcontroller is calibrated to disable operation of the capacitive sensors when the flex sensor is engaged and therefore, at one given time the maximum number of haptics that are enabled will be two haptic motors.

3.3. DESIGN OUTCOMES AND SPECIFICATIONS

Table 3.1
Power Consumption of the Sensory Feedback System.

| Component | Quantity | Voltage, V (V) | Current, I (mA) | Power Consumption, W (W) |
|--|----------|-------------------|--------------------------------------|---|
| Arduino Pro Mini (with Capacitive Sensors and Flex Sensor) | 1 | 3.3 | 9.6 | 0.03168 |
| Vibration Motor Disc (Haptic) | 3 | 3.3 | 81.6 (1 haptic) 163.2 (2 haptics) | 0.26928 (1 haptic) 0.53856 (2 haptics) |

Since only a maximum of two haptic motors can operate at any given time, the worst case scenario power consumption of the device would be when the current is 172.8 mA (from Table 3.1: 9.6 + 163.2 mA). Therefore, at worst case scenario where the 2500 mAh battery is chosen; the battery would be able to supply power for a maximum of 14.47 hours as shown in Equation 3.4.

The 2500 mAh battery would be able to supply power to the system in an idle state for 260.4 hours (10.85 days) as shown in Equation 3.5. At maximum power consumption (i.e. when a maximum of two haptic motors are operating 100% of the time), the battery would be able to supply power to the system for 14.47 hours but since this would be the worst case scenario and due to the design of the system (where the capacitive sensors are turned off if operated at 100% for more than 3 seconds), it is highly unlikely that two haptic motors would be operating at 100% for 14.47 hours.

$$\text{Worst case scenario} = \frac{2500 \text{ mAh}}{9.6 \text{ mA} + 163.2 \text{ mA}} = 14.47 \text{ hours} \quad (3.4)$$

$$\text{Idle state} = \frac{2500 \text{ mAh}}{9.6 \text{ mA}} = 260.4 \text{ hours} = 10.85 \text{ days} \quad (3.5)$$

Therefore, it is evident that a 3.7 V 2500 mAh Li-Poly would be sufficient to power the system. Figure 3.10 presents an image of the chosen battery. It is 47 x 61 x 6.7 mm and 43 grams.



Figure 3.10: 3.7 V Lithium Polymer 2500 mAh Rechargeable Battery.

The pins of the Arduino Pro Mini have the capability to supply a maximum of 40 mA. The haptic motors require at least 60 mA (80 mA maximum) each to function (with a peak start-up current draw of 120 mA). Therefore, they cannot be powered directly by the Arduino pins without causing significant damage. Transistors can; however, be used to switch the power ON and OFF to the haptics. The power supply of the Arduino Pro Mini has a maximum of 200 mA capability. To avoid exceeding the limit of this power supply, a voltage regulator (LM317T from STMicroelectronics) was used to supply power to the complete circuit. A voltage regulator will ensure that a constant output voltage is supplied to the microcontroller and haptics regardless of slight changes to the input voltage or load conditions specific to the battery. The haptics drew power directly from this power supply whilst being switched ON and OFF by the transistor. The transistors (IRLML6344TRPbF from International Rectifier) used are rated at 2A.

3.3.3 Embodiment of the System

3.3.3.1 Concept Generation and Selection

Figure 3.11 presents the various concepts generated and explored in the design of the embodiment of the system. Upon first review of the generated concepts, those highlighted in red were immediately excluded as they were deemed to meet one or more of the following criteria:

- This would increase the regulatory risk of the project due to its invasive (injection, pill, microchip implant) or controversial nature (pig intestine sleeve), and/or

3.3. DESIGN OUTCOMES AND SPECIFICATIONS

- This would increase the complexity of the project outside of the outlined scope for a minor dissertation (injection, pill, microchip implant, pig intestine sleeve, wrist strap with hologram, drone).

Table 3.2 presents an evaluation of the remaining concepts (highlighted in orange and green in Figure 3.11). It is evident from the analysis presented in the table that some concepts are better suited as the embodiment of the feedback portion of the device and others are better suited as the embodiment of the sensing portion of the device. The embodiment for the feedback portion of the system is described in more detail in Section 3.3.3.3.

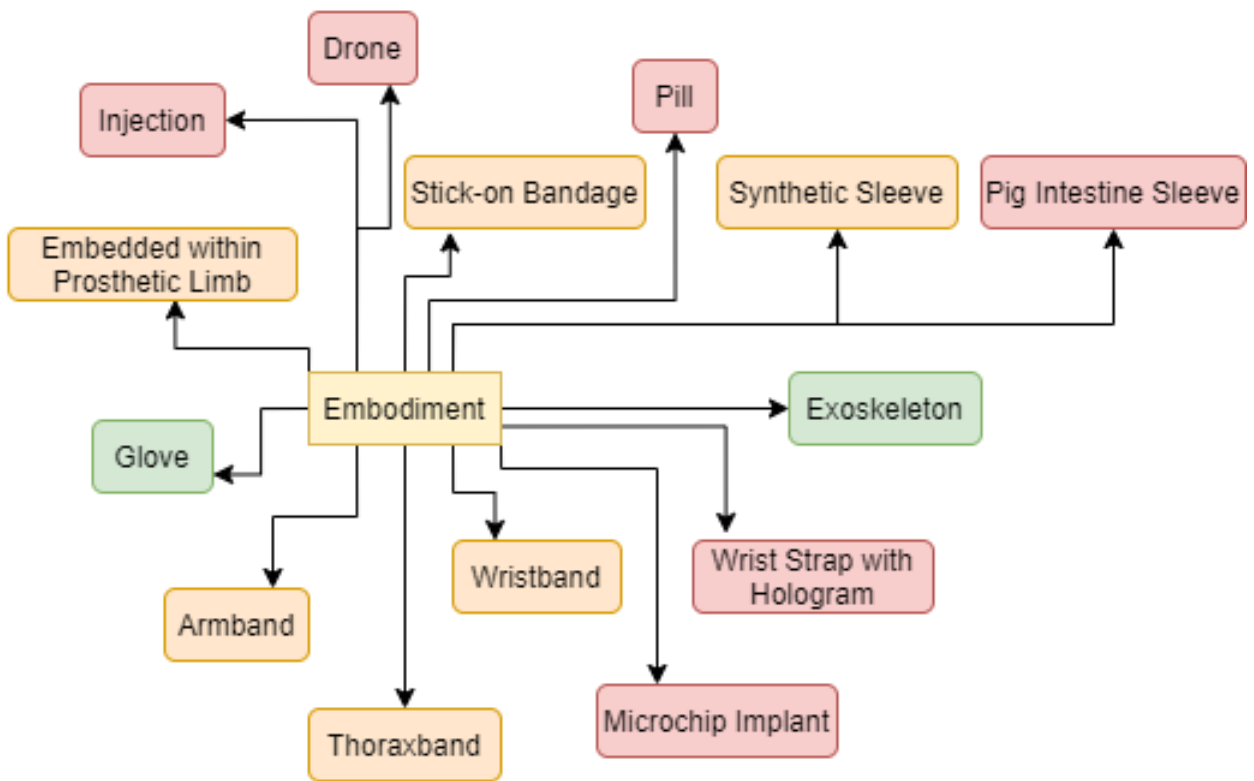


Figure 3.11: Concept Ideas Generated for the Embodiment of the System.

3.3. DESIGN OUTCOMES AND SPECIFICATIONS

Table 3.2

Evaluation of Remaining Concept Parameters for the Embodiment of the System

| Embodiment Concept | Suitability | Removed |
|---------------------------------|--|----------------|
| Armband | This appears to be a viable embodiment concept for feedback which would need to be used in conjunction with another embodiment concept suitable for sensing. | |
| Wristband | This appears to be a viable embodiment concept for feedback which would need to be used in conjunction with another embodiment concept suitable for sensing. | |
| Thorax-band | This appears to be a viable embodiment concept for feedback which would need to be used in conjunction with another embodiment concept suitable for sensing. | |
| Glove | This appears to be a viable embodiment concept for sensing which would need to be used in conjunction with another embodiment concept suitable for feedback. | |
| Synthetic Sleeve | This concept is deemed ineffective as it would involve exclusion of the hand portion which is the most important aspect in terms of sensing for this project. | X |
| Stick-on Bandage | This would require an adhesive surface on which to stick which raises questions as to how reliable this solution would be. One cannot have the risk of the device falling off in the middle of the day because the stick-on force wasn't large enough. | X |
| Embedded within Prosthetic Limb | This solution would exclude the very people this project aims to help: trans-radial amputees who already use prostheses. If the solution is in the form of another prosthetic limb, chances are there will be limited funding for an additional purchase of a prosthesis. Design of a prosthetic limb is out of the scope of this project. | X |
| Exoskeleton | This appears to be a viable embodiment concept for sensing which would need to be used in conjunction with another embodiment concept suitable for feedback. | |

3.3. DESIGN OUTCOMES AND SPECIFICATIONS

Two concepts were taken further into rapid prototyping to explore the embodiment of the sensing portion of the system: one, a glove-like embodiment and two, an exoskeleton-like embodiment. Other concepts explored before rapid prototyping began pertaining to the feedback portion of the device included: the armband, wristband and thorax-band as described in Table 3.2 and shown in Figure 3.11.

Both a silicone glove and a glove made of synthetic material were explored during rapid prototyping. Figure 3.12 and 3.13, and 3.14 and 3.15 present computer aided design (CAD) images of these concepts, respectively. In parallel with exploring these two concepts, a soft exoskeleton was also explored. Figure 3.16 presents the CAD image of the soft exoskeleton. All three concepts operate with the same principle that the capacitive sensors would be embedded within the chosen material (either silicone, synthetic material or 3D printable material), and that the flex sensor would be embedded or connected to the system and placed on one of the appropriate fingers as explained in Section 3.3.2. For the silicone and synthetic glove concepts, the vibration motors are embedded within the proximal portion of the glove (the portion which makes contact with the residual portion of the limb). For the soft exo-skeleton, the vibration feedback is in the form of a vibro-tactile armband located on the upper arm which will further be explained in Section 3.3.3.3.

The manufacturability of the device was a key factor for determining the final design. Design for manufacturability is in essence how easy something is to manufacture. Taking manufacturability of the design into consideration, it was decided that the soft 3D printable exoskeleton concept was more optimised for manufacture than the silicone and synthetic glove concepts. Its design details are further described in Section 3.3.3.2.

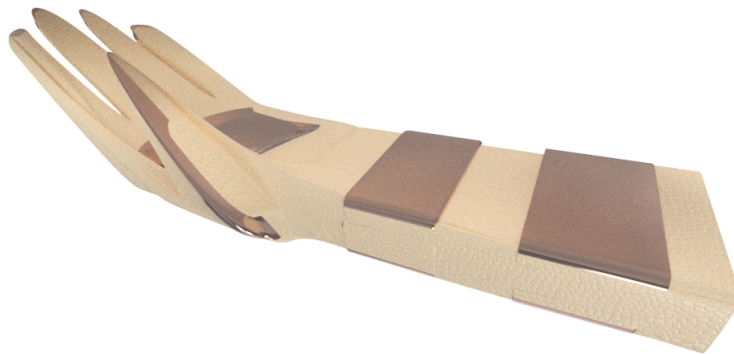


Figure 3.12: CAD Image of the Concept for a Silicone Glove (Capacitive Sensors in Copper).

3.3. DESIGN OUTCOMES AND SPECIFICATIONS



Figure 3.13: CAD Image of the Concept for a Silicone Glove (Capacitive Sensors in Copper) (Side View).

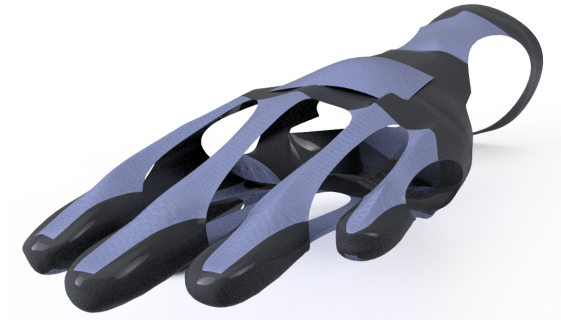


Figure 3.14: CAD Image of the Concept for a Synthetic Glove (Capacitive Sensors in Purple).

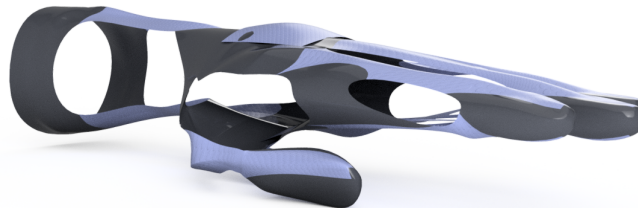


Figure 3.15: CAD Image of the Concept for a Synthetic Glove (Capacitive Sensors in Purple) (Side View).

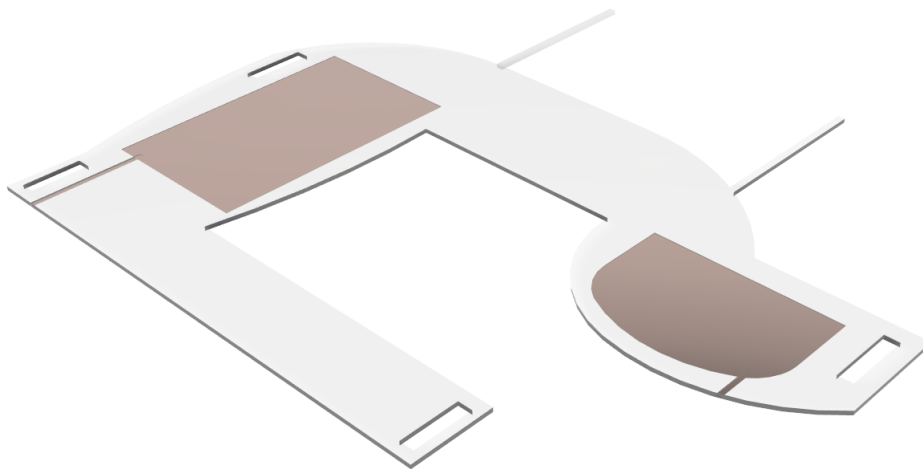


Figure 3.16: CAD Image of the Concept for a Soft Exoskeleton (Capacitive Sensors in Copper)).

3.3.3.2 Final Embodiment of the Sensory System

From Section 3.3.3.1 above, the soft exoskeleton as the embodiment of the system was chosen as presented in Figure 3.16. Thermoplastic Polyurethane (TPU) was chosen as the material for 3D printing for its high durability and flexibility allowing for a design that easily wraps around the prosthetic device without hindering its original functionality or damaging the integrity of the sensory feedback system. Other advantages of this material include its resistance to: oils, grease and solvents, abrasions and scratches, robust weather and high-energy radiation (and ultraviolet light) (Omnexus, 2021). The two thin protrusion in Figure 3.3.3.1 are the attachments to connect to the flex sensor embodiment described below.

The flex sensor portion of the embodiment was also designed with TPU chosen for similar reasons. It was important that the integration of the flex sensor with the prosthetic device did not hinder the intended functionality of the prosthesis. Any slight restriction or restrictive force applied to the prosthetic hand's fingers, during bench testing, as it attempted to bend would stop it from doing so. Furthermore, a flex sensor will ultimately measure the bend but it is important to protect the sensor from bending too far which was crucial in the design of this embodiment. Table 3.3 presents a review of the design iterations explored for the flex sensor embodiment. Figure 3.17 presents all six of the 3D printed design iterations. Figure 3.18 presents a close-up of design iterations 5 and 6 (final) to illustrate the guiding structure.

Figure 3.19 and 3.20 illustrate the prosthetic in finger flexion without the flex sensor embodiment and with the flex sensor embodiment. The figure emphasises that the presence of the flex sensor embodiment and flex sensor does not hinder the original movement of the prosthetic finger to which it is attached.

Table 3.3

Review of the Design Iterations for the Flex Sensor Embodiment.

| Design Iteration | Key Features | Design Considerations | Problems |
|------------------|--|--|--|
| 1 | <p>- Two large rings with two thin columns of 2 mm width joining the rings together.</p> | <p>- Minimal tolerance between diameter size of fingers and large rings to keep the embodiment in space stiffly on the finger.</p> <p>- Two columns joining the large rings of 2 mm width (thinness allowed finger to bend as intended without applying any resistance to the function whilst also connecting the large rings to each other.</p> | <p>- No consideration for flex sensor.</p> |

Table 3.3
Review of the Design Iterations for the Flex Sensor Embodiment.

| Design Iteration | Key Features | Design Considerations | Problems |
|-------------------------|---|---|---|
| 2 | - Design iteration 1 with the addition of a semi-circular structure on the distal (top) ring to keep flex sensor in place. | - Semi-circular structure was intended to keep the flex sensor in position but also allow it to slide up and down as the finger flexed and extended. | - Flex sensor frequently fell out of the distal semi-circular structure as it slid up and down during flexion and extension and could not return in to the structure. |
| 3 | - Design iteration 2 with the addition of another semi-circular structure on the proximal (bottom) ring to guide the flex sensor as it moved up and down. | - Second semi-circular structure was intended to further keep the flex sensor in place and guide it as it moved up and down as the finger flexed and extended as with design iteration 2. | - Flex sensor was bending too far during flexion of the finger and the way it bent was not realistic to how the prosthesis finger bent. |

Table 3.3
Review of the Design Iterations for the Flex Sensor Embodiment.

| Design Iteration | Key Features | Design Considerations | Problems |
|-------------------------|--|--|---|
| 4 | - Design iteration 3 with the addition of a third large half-ring, between the two original large rings, with its own semi-circular structure. | - Third half-ring allows the flex sensor to bend in a smoother pattern and the semi-circular structure guides the flex sensor as the finger is flexed and extended. | - Flex sensor frequently fell out of the distal semi-circular structure as it slid up and down during flexion and extension and had difficulty returning to it. |
| 5 | - Design iteration 4 with the addition of a guiding structure (an extension of the distal semi-circular structure upwards). | - Guiding structure was intended to keep the flex sensor within the semi-circular structure as the finger flexed and extended causing the sensor to slide up and down. | - Flex sensor still often fell out of the distal semi-circular structure. |

Table 3.3

Review of the Design Iterations for the Flex Sensor Embodiment.

| Design Iteration | Key Features | Design Considerations | Problems |
|-------------------------|---|--|-----------------|
| 6 (Final) | - Design iteration 5 with the addition of a further extrusion downwards of the guiding structure. | - Extension of the guiding structure was intended to keep the sensor in line and prevent it was sliding out as the sensor slides up and down during flexion and extension. | - None. |

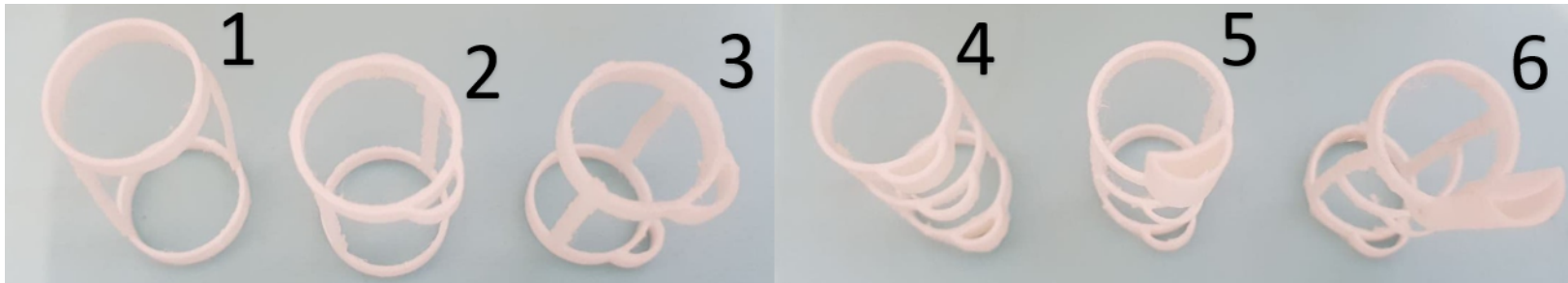


Figure 3.17: Design Iterations for the Flex Sensor Embodiment (Left to Right: 1, 2, 3, 4, 5, and 6 (final)).

3.3. DESIGN OUTCOMES AND SPECIFICATIONS

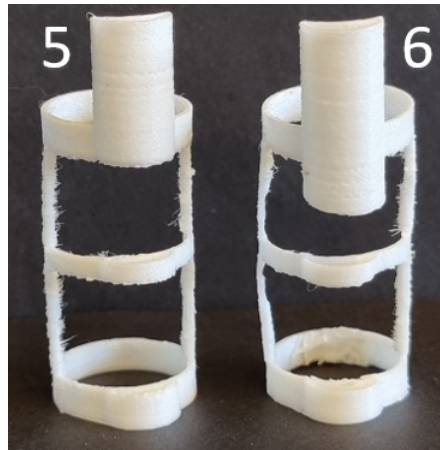


Figure 3.18: Close-up of Design Iterations 5 (Left) and 6 (Right).

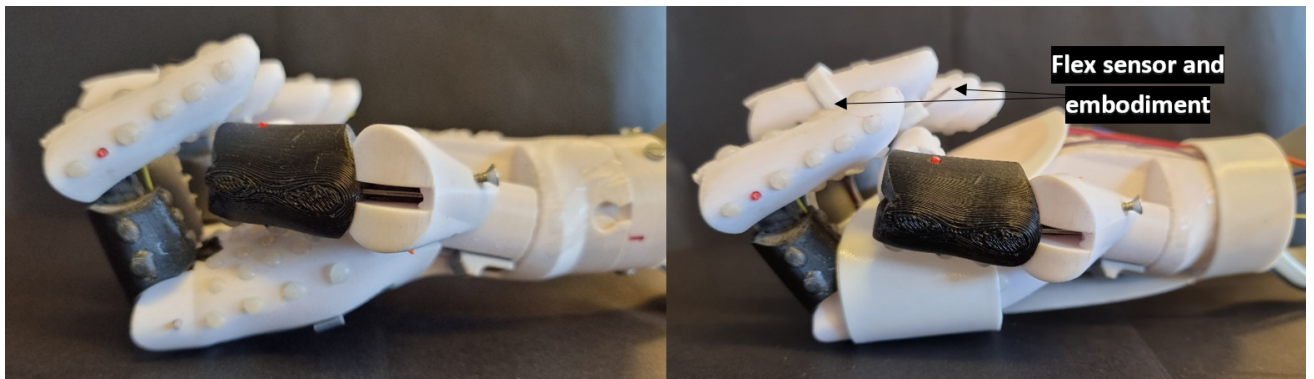


Figure 3.19: Finger Extension of Prosthesis without Flex Sensor Embodiment (Left) and with Flex Sensor Embodiment (Right).



Figure 3.20: Finger Extension of Prosthesis without Flex Sensor Embodiment (Left) and with Flex Sensor Embodiment (Right).

3.3.3.3 Final Embodiment of the Feedback Mechanism

As stated in Section 3.2.1.2, vibrotactile stimulation was chosen as method of feedback.

The closed-loop vibrotactile interface consists of a wearable device presented in Figure 3.21, 3.22 and 3.23. The wearable armband embeds three vibration (haptic) motor discs (Pololu Electronics Shaftless Vibration Motor 10 x 2 mm, 75 g, 3 V) on separate haptic enclosures as seen in the figures.

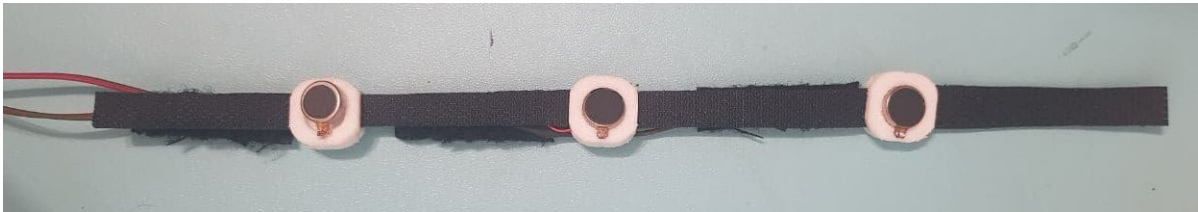


Figure 3.21: Front View of Vibrotactile Armband.

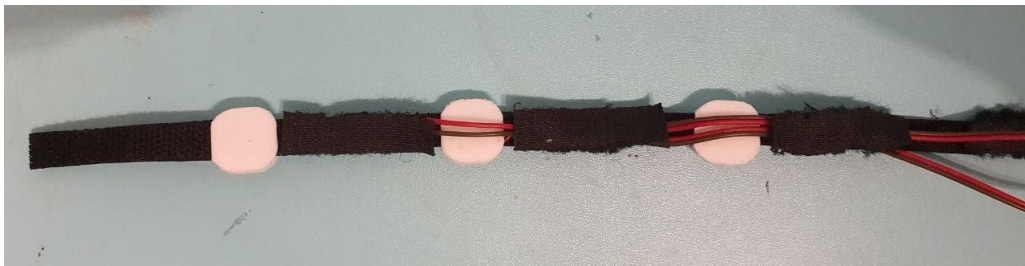


Figure 3.22: Back View of Vibrotactile Armband.



Figure 3.23: Vibrotactile Armband on Participant Upper Arm.

The haptic enclosures are designed such that they can move on the armband so that the haptic discs can be proportionally spaced apart depending on the diameter of the participant's upper arm. The haptic enclosures were 3D printed in thermoplastic

3.3. DESIGN OUTCOMES AND SPECIFICATIONS

polyurethane (TPU) using the Ultimaker 2+. This material was chosen for its high durability and particularly its flexibility which makes the haptic enclosures slightly softer in texture compared to a print done in harder materials like acrylonitrile butadiene styrene (ABS) or polylactic acid (PLA). The desire for the softer texture of TPU opposed to a harder texture like PLA or ABS is increased comfort for the user. The design iterations for the haptic enclosure are presented in Figure 3.24, 3.25 and 3.26 and Table 3.4 summarises the improvements between iterations. To further enhance comfort, the haptic enclosures were given a 6 mm fillet all-round to avoid sharp points or edges digging in to the skin of the user (the rounder haptic enclosures in the figures are the ones with the fillet applied). Furthermore, a portion of the enclosure was extruded to accommodate wiring from the haptic motors. This creates a safe path to route the wiring away from the user.

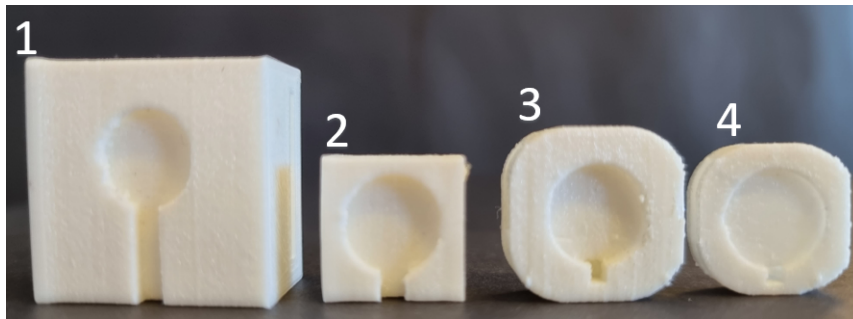


Figure 3.24: Front Image of the Design Iterations for the Haptic Enclosure (Left to Right: Iteration 1, 2, 3 and 4).

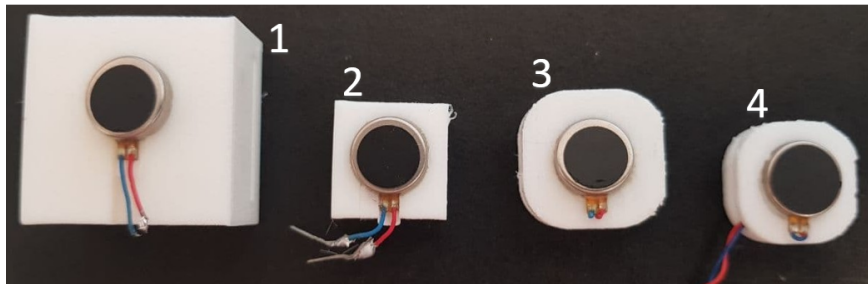


Figure 3.25: Front Image of the Design Iterations for the Haptic Enclosure with Haptics Inserted (Left to Right: Iteration 1, 2, 3 and 4).

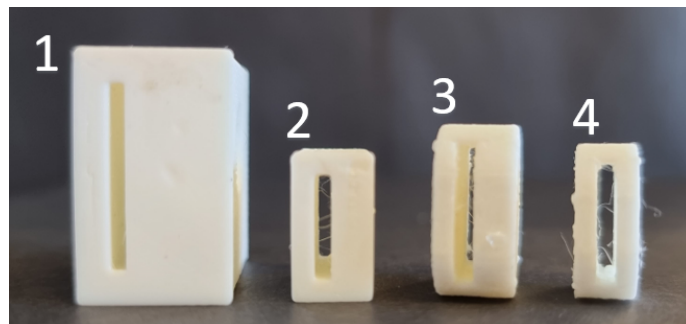


Figure 3.26: Side Image of the Design Iterations for the Haptic Enclosure (Left to Right: Iteration 1, 2, 3 and 4).

3.3. DESIGN OUTCOMES AND SPECIFICATIONS

Table 3.4

Review of the Design Iterations for the Haptic Enclosure.

| Design Iteration | Key Features | Improvements |
|------------------|---|---|
| 1 | <ul style="list-style-type: none"> - Extrusion for haptic disc to sit with routing for wiring - Extrusion for strap | None |
| 2 | <ul style="list-style-type: none"> - Much smaller in area and volume than first iteration - Extrusion for haptic disc to sit with routing for wiring - Extrusion for strap | <ul style="list-style-type: none"> - Less material is used (time to print minimised) - Consideration for strap |
| 3 | <ul style="list-style-type: none"> - Much smaller in area and volume than first iteration (similar size to second iteration) - Rounding of the edges (fillet of 6 mm) to maximise user comfort - Extrusion for haptic disc to sit with routing for wiring that allows for the wiring to be routed through the extrusion for the strap - Extrusion for strap | <ul style="list-style-type: none"> - Less material is used (time to print minimised) - More effective means of routing the wiring (safer) - Consideration for strap |
| 4 (Final) | <ul style="list-style-type: none"> - Much smaller in area and volume than first iteration (similar size to second and third iterations but still smaller) - The final design was made slightly thinner than the third iteration - Rounding of the edges (fillet of 6 mm) to maximise user comfort - Extrusion for haptic disc to sit with routing for wiring that allows for the wiring to be routed through the extrusion for the strap - Extrusion for strap | <ul style="list-style-type: none"> - Even less material is used (time to print minimised) - More effective means of routing the wiring (safer) - Consideration for strap |

3.3.4 Preliminary Design Validation to Prove Proof-of-Concept of the Capacitive Sensor-Vibration Feedback Combination

Preliminary bench testing of the capacitive sensors described in Section 3.3.1.1 indicate that a wide range of materials can be detected by them; however good electrical conductors such as human skin, wood and metal interact with the sensors with the most success. Less conductive materials such as ceramic and glass do not fair as well as the more conductive materials (metal, human skin and wood). It is evident from preliminary bench testing that if bad electrical conductive materials are not coated with specific coatings (that are good electrical conductors); the sensors are unable to detect the materials in terms of proximity but can detect some variations of touch. For example, the sensors can easily detect a ceramic mug that has been coated with a protective paint containing metal.

Four able-bodied, adult volunteers (three males and one female; mean age 25.72 ± 0.96 [*mean \pm standard deviation*])) participated in a study conducted at the University of Cape Town in the Medical Devices Lab to test the proof-of-concept of the capacitive sensor-vibration motor disc combination. None of the volunteers had previous experience with the sensory feedback proof-of-concept which consists of four capacitive sensors enclosed in silicone placed on a 3D printed static (unable to move) prosthetic hand and a vibration feedback mechanism consisting of four Velcro finger straps which each house a vibration motor disc. Figure 3.27 presents the capacitive sensors on the prosthetic hand and Figure 3.28 illustrates the finger straps. As can be seen in Figure 3.28, yellow LEDs were connected to the finger straps which were coded in the same way the vibration motor discs were (i.e. if the haptic disc was vibrating at 50% of its capacity then the brightness of the LED would shine at 50% of its capacity, too). This was done to allow the moderator of the testing session to compare the answers that were given by the participant to what the device was actually doing. It was implemented to aid in demonstrations where one person could be connected to the device but any one else in the room was able to see the workings of the device. It also assisted during bench testing and calibration of the sensors.



Figure 3.27: Capacitive Sensors Embedded within Silicone Placed on the 3D Printed Static Prosthetic Hand.

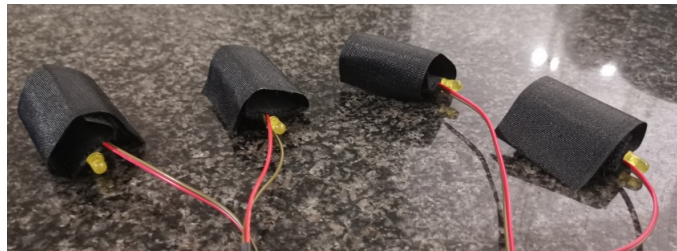


Figure 3.28: Velcro Finger Straps with Vibration Motor Discs Inside and LEDs.

Prior to commencement of the study, participants were given a description of the workings of the device and were shown how the device worked. This allowed them to become familiar with the device operation and with the different vibration intensities (lower intensity vibration for proximity, medium intensity vibration for slight contact with the sensor and highest intensity vibration for harder contact with the sensor, vibration intensity increases as an object moves closer and decreases as it moves away). Participants were blindfolded during the test to ensure no visual cues affected the results of the study. No noise-cancelling device was used in this study as the vibration motors vibrated within a Velcro strap which dampened the noise they made as they vibrated and the finger straps were kept at a distance away from the ears deemed sufficient not to aid the participant with auditory cues enough to affect the results of the study.

3.3. DESIGN OUTCOMES AND SPECIFICATIONS

Figure 3.29 illustrates the range of materials that were used for testing. The intention was to use common items or materials found in and around the house. This included: two wooden cutting boards, a metal fork and spoon, two ceramic mugs from different brands, two glasses from different brands and the hand of the moderator.



Figure 3.29: Materials used for Testing.

The test was divided into five sections whereby each material (human, metal, wood, ceramic and glass) was presented to them. When an object was presented to them, participants were asked to identify the location/s on the hand that was/were being stimulated (dorsum of the hand, palm of the hand, anterior forearm or posterior forearm), the state of the interaction at each location (proximity - low intensity vibration, light touch - medium intensity vibration or hard touch - high intensity vibration) and whether the object was moving closer to or away from the stimulated sensor/s (moving towards was illustrated by a gradual increase in the vibration intensity and moving away by a decrease). The form used to record the raw data during testing can be viewed in Appendix A.5.

Results indicated that all four participants achieved 100% for tasks detailed in the form in Appendix A.5 using human skin and metal. For tasks involving wood, all four of the participants could tell the difference between proximity and touch but sometimes had difficulty distinguishing between light and hard touch. However, all four could tell when the wooden object was moving towards the sensor/s or away from them and locate the stimulated sensor/s. For tasks involving ceramic (characteristically a bad electrical conductor), it depended largely on the coating of the object. The two mugs that were used during testing were detectable by the sensors (although the grey one always faired better than the other due to its more metallic protective coating). Therefore, all four participants could locate the stimulated sensor/s and tell whether the object was moving towards the

sensor/s or away from the sensor/s. As for wood, the participants showed difficulty in distinguishing between light and hard touch but could always tell the difference between proximity and touch. Glass faired poorly as the sensors had difficulty detecting the material as it was not coated with any special metallic coatings. Whilst participants could locate the stimulated sensor/s accurately, the only state of the haptic that was reported was proximity. Participants were unable to say whether the glass was moving towards or away from the sensor/s.

Detection distance (proximity range) varied with different materials: good conductors of electricity could be detected by the sensors from at least 4 cm away; however, poorer conductors were able to be detected from approximately 1 to 2 cm away (and sometimes not at all, unless physically touching the sensor).

3.3.5 Integrated System

A custom printed circuit board (PCB) was designed and manufactured to mechanically support and electrically connect the electronic components chosen for the final prototype of the sensory feedback system. The custom PCB used for the final prototype is presented as CAD images in Figure 3.30 and 3.31, and images of the physical board are presented in Figure 3.32 and 3.33. It was designed to be as compact as possible and therefore, the size was determined largely by the size of the battery. The dimensions of the PCB was 85 x 40 x 2 mm. Figure 3.33 illustrates the PCB next to the battery. The electronic schematic of the PCB can be viewed in Appendix A.3.

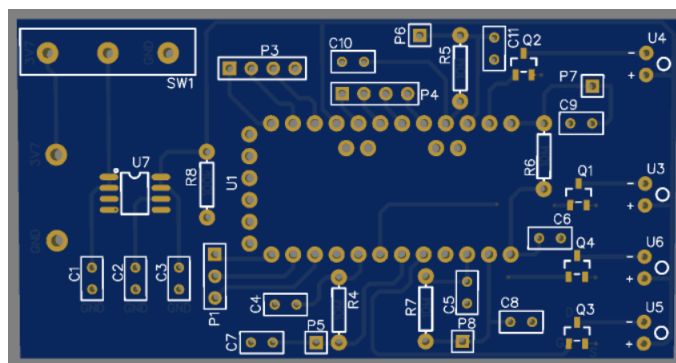


Figure 3.30: CAD Image of the Front of PCB.

3.3. DESIGN OUTCOMES AND SPECIFICATIONS

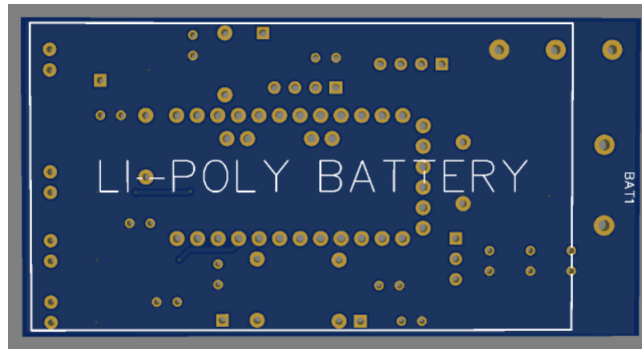


Figure 3.31: CAD Image of the Back of PCB.

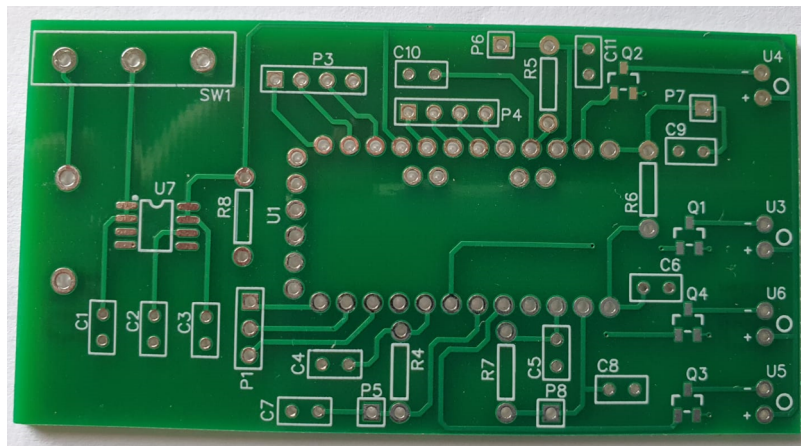


Figure 3.32: Front Image of Physical PCB used for Prototyping.

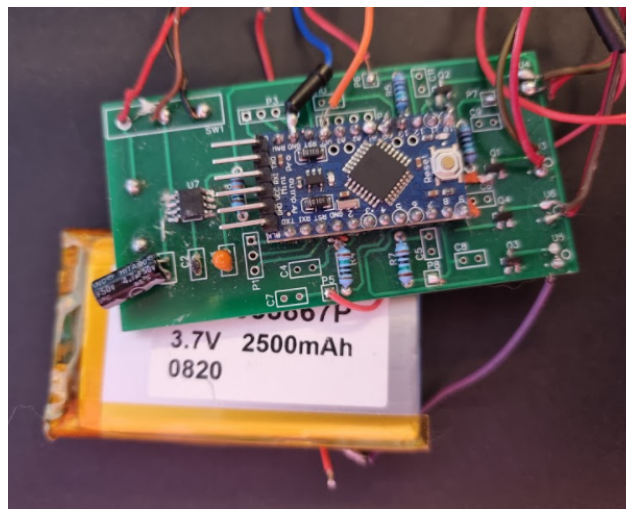


Figure 3.33: Image of Physical PCB used for Prototyping.

According to research, adding a small capacitor (around 100 pF) from the sensor pin to ground improves both stability and repeatability. Adding small capacitors that range between 20 and 400 pF in parallel with the body capacitance also stabilises the readings

3.3. DESIGN OUTCOMES AND SPECIFICATIONS

of the sensor (Badger, 2008). This was accounted for in the design of the PCB in case the readings obtained from the capacitive sensors required additional stabilisation.

An electronic housing was designed and 3D-printed in ABS using the Ultimaker 2+ to provide housing for the electronic components not embedded within the embodiment of the system. The electronic housing is presented in Figure 3.34 and houses a printed circuit board (PCB) on which the Arduino Mini Pro and the ancillary electronic components (transistors, resistors, voltage regulator, capacitors and connection of various wires linked to the sensors and haptic motor discs) sit. The housing also has accommodation for the ON/OFF switch of the device as on the box on the left seen in Figure 3.34. A finger grip was incorporated in the lid design to make opening and closing the enclosure easier as seen in Figure 3.34 on the right. ABS was chosen for its durability, impact resistance and strength to ensure maximum protection for the contents found within the housing. Additionally, ABS has a higher glass transition temperature. This means that the material can withstand higher temperatures before it begins to deform and; therefore, is suited for housing electronic components which may become slightly warm when in operation.

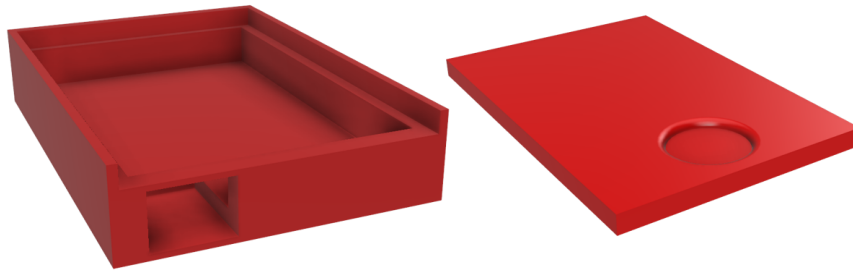


Figure 3.34: CAD of Electronic Housing (Left: Box, Right: Lid).

The final dimensions of the capacitive sensors were such that they optimised the allocated area of either the palm or the dorsum of the embodiment. The palmar capacitive sensor is a rectangle with dimensions: 72 x 44 mm, and the dorsal capacitive sensor is an unconventional shape with largest dimensions: 52 x 34 mm. The capacitive sensors were embedded half-way through the thickness of the embodiment. The thickness of the embodiment was 1 mm. The chosen embodiment of the system was described in detail in Section 3.3.3; however, Figure 3.35 illustrates how the custom capacitive sensors were embedded within the chosen embodiment design. This figure presents a longitudinal section of the embodiment taken 0.4 mm from the top surface.

The complete code compiled on to the Arduino Mini Pro is presented in Appendix A.4. Figure 3.36 and 3.37 present detailed flowcharts of the workings of the software designed for the system. The main logic as shown in Figure 3.36 checks the status of each capacitive sensor first. If an object is in proximity to or in contact with the sensor, the haptic connected to the respective sensor is set accordingly. Figure 3.37 on the left presents

3.3. DESIGN OUTCOMES AND SPECIFICATIONS

in detail how the haptics are set for the capacitive sensors. If a capacitive sensor is triggered in hard touch condition for longer than a period of 2 seconds, the haptics will automatically be turned OFF to avoid irritation to the user (timing for this is kept for a peripheral interrupt sequence). After the capacitive sensors, the flex sensor is evaluated. If the flex sensor is triggered, both capacitive sensors are turned OFF to allow the user to focus on the haptic of the flex sensor. The haptic of the flex sensor is set accordingly. Figure 3.37 on the right shows in detail how the range of the haptic is chosen for the flex sensor. The haptic motors have an adaptable intensity (rather than a fixed threshold value) which means that the intensity is varied by applying a lower or higher voltage to them which correlates to the state of the respective capacitive or flex sensor.

The complete integrated closed-loop sensory feedback system is presented in Figure 3.38 and 3.39. The embodiment of the system takes a total of 23 grams of TPU materials to print (1 gram for the flex sensor embodiment and 22 grams for the rest) and a total duration of 4 hours and 24 minutes (44 minutes for the flex embodiment and 3 hours and 40 minutes for the rest) when printed at high, fine quality (0.1 mm layer height and 40 mm/s print speed).

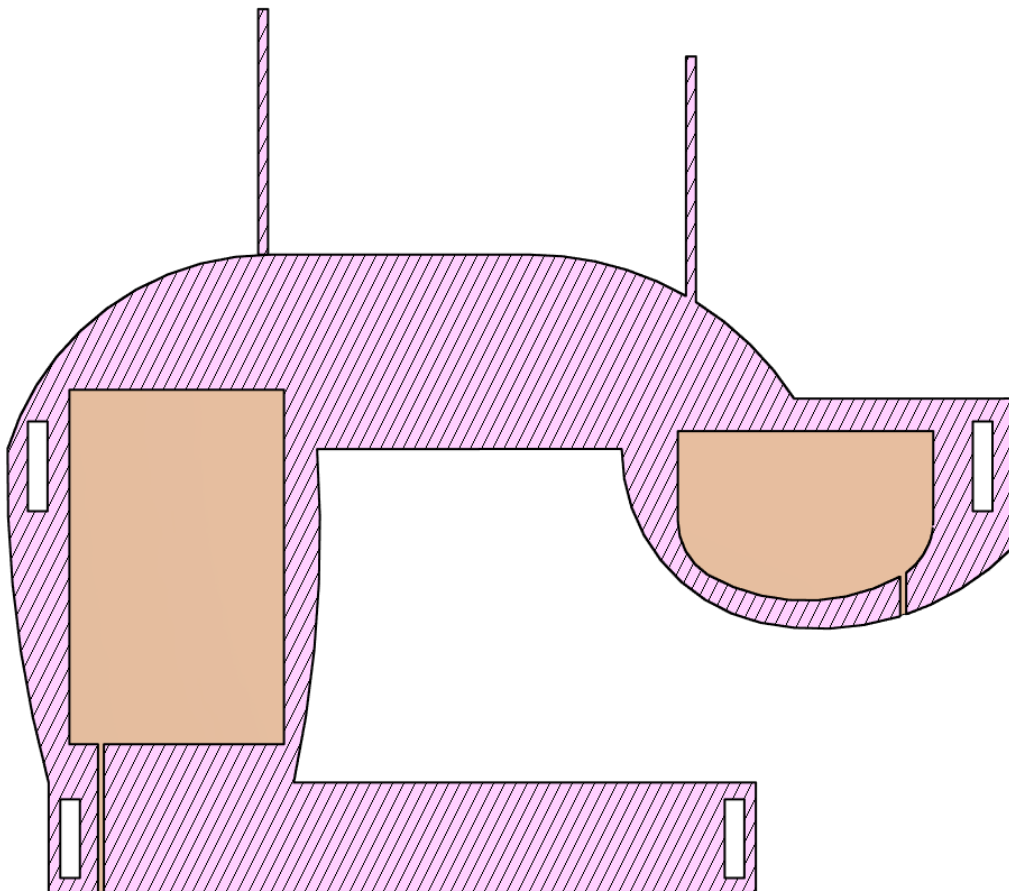


Figure 3.35: Longitudinal Section of the Embodiment to Illustrate the Embedded Capacitive Sensors (Copper).

3.3. DESIGN OUTCOMES AND SPECIFICATIONS

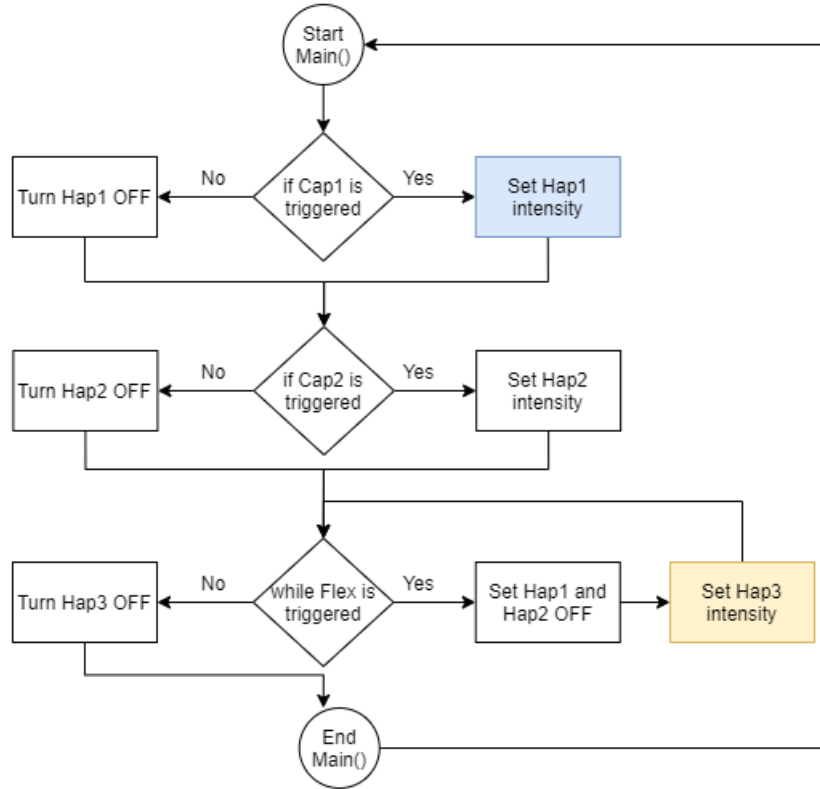


Figure 3.36: Program Flowchart for Sensory Feedback System.

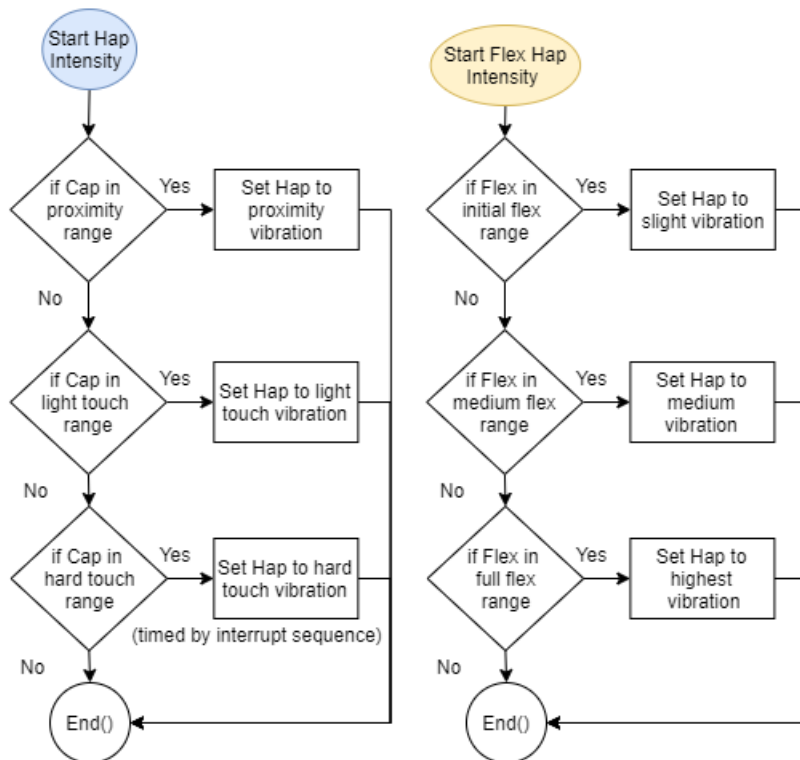


Figure 3.37: Program Function Flowchart for Haptic Intensity for: Capacitive Sensors (Left) and Flex Sensor (Right).

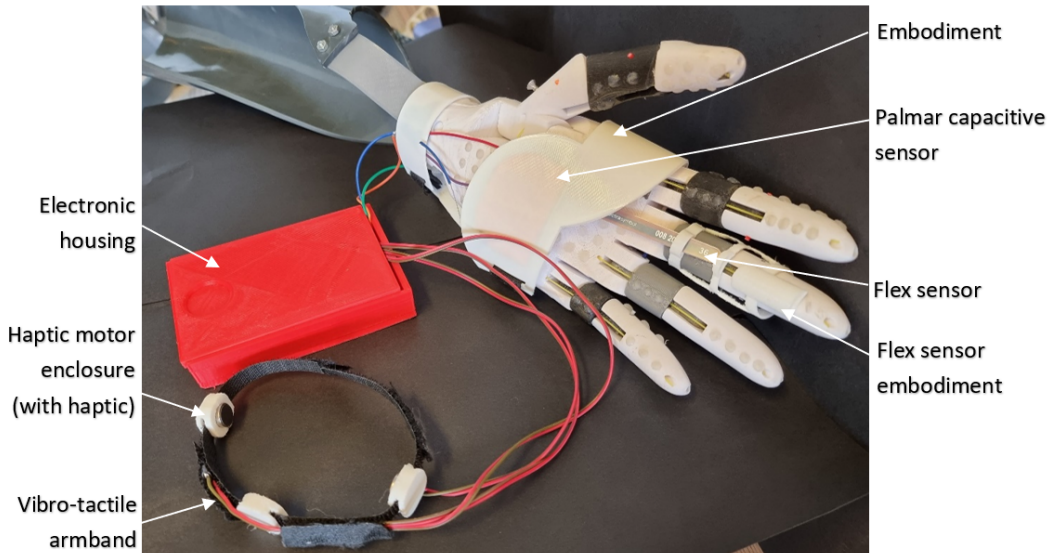


Figure 3.38: Complete Integrated Closed-Loop Sensory Feedback System (Palm View).

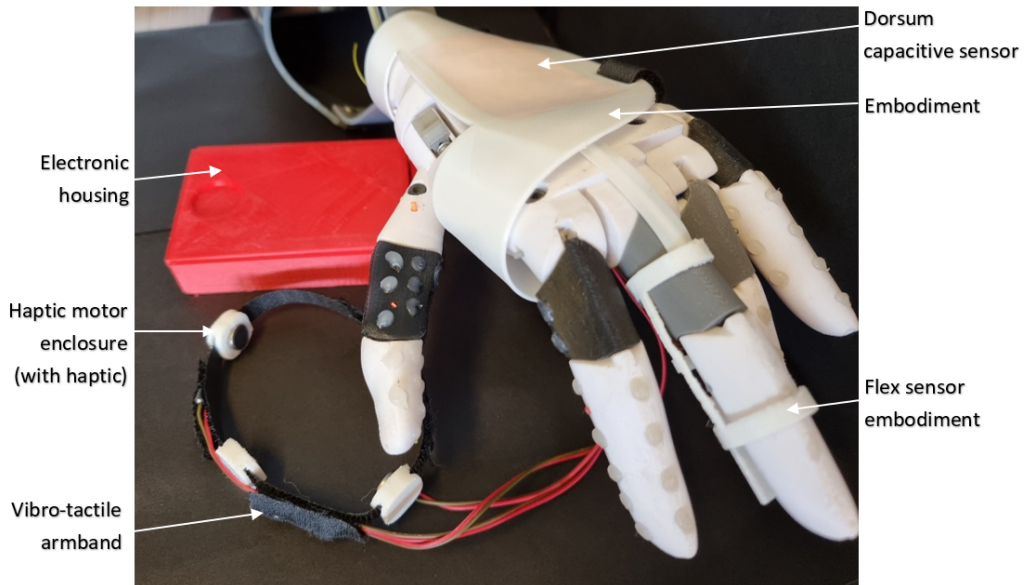


Figure 3.39: Complete Integrated Closed-Loop Sensory Feedback System (Dorsum View).

3.3.6 Design Specifications

Table 3.5 presents a summary of the design specifications for the device described throughout this chapter. It presents the design requirement for each subsystem/system parameter and illustrates how these were successfully achieved.

Further testing to validate the design of the system is described in Section 4.4. This design validation will focus on the last design requirement for the feedback mechanism:

- The system is to provide the user with increased tactile and proprioceptive awareness demonstrated by improved results in an OISD test, improved results in confidence levels and improved response times.

Table 3.5
Summary of Design Specifications of the Sensory Feedback System.

| System Component | Design Requirement (Target) | Successful? | Design Outcome/Specification (Actual) |
|-------------------|--|-------------|---|
| Sensing Mechanism | <ul style="list-style-type: none"> - The chosen sensor/s must be able to detect range of objects within 4 cm proximity to the prosthesis. - The chosen sensor/s must be able to detect when the hand is in contact with an object. - The chosen sensor/s must be able to detect a range of positions of the fingers (from fully extended to fully bent; i.e. detect the angle between the palm of the hand and the fingers that ranges between 180° and 90° as this is the range of motion of the prosthetic hand fingers). | Yes | <p>Custom Capacitive Sensors and Flex Sensor (SparkFun)</p> <ul style="list-style-type: none"> - The capacitive sensors are able to detect certain materials within 4 cm proximity (human skin, metal, wood, cement, ceramic and glass (when coated with metallic enhancements like sliding doors, mugs with metallic protective paint etc.)). - The capacitive sensors are able to detect (for the objects stated above when the hand is in contact with an object. - The flex sensor is able to detect finger movements ranging between when the finger is fully extended (180°) and when the finger is fully flexed (90°) |

Table 3.5
Summary of Design Specifications of the Sensory Feedback System.

| System Component | Design Requirement (Target) | Successful? | Design Outcome/Specification (Actual) |
|--------------------|--|-------------|---|
| Feedback Mechanism | <ul style="list-style-type: none"> - The feedback system is to have a proportional circular arrangement. - The feedback system is to have variation in intensity capabilities. | Yes | <p>Vibrotactile Armband with Haptic Motors (Pololu Elect.)</p> <ul style="list-style-type: none"> - The haptic motors are arranged in a proportional circular arrangement. - The haptic motors have variation in intensity capabilities (can be programmed to present a range of vibration intensities). |
| Power Supply | <ul style="list-style-type: none"> - The size and weight of the power supply must be minimised for integration with the system such that no significant weight or volume is added to the prototype. - The power source must be rechargeable within 6 hours (within a user's proposed sleeping cycle). - The power source must be able to supply power to the system for at least 18 hours (the period of time for which the user would be awake). - The power source must be mobile and easy to integrate within the system. | Yes | <p>3.7 V 2500 mAh Lithium-Polymer Battery</p> <ul style="list-style-type: none"> - Rechargeable in under 6 hours. - Able to supply power to the system for at least 18 hours. - Power supply is mobile and easy to integrate within the system (connect the terminals to the PCB). - The dimensions of the battery are 47 x 61 x 6,7 mm and it is 43 g (minimal size or volume, no significant weight or size increase to the prototype). |

Table 3.5
Summary of Design Specifications of the Sensory Feedback System.

| System Component | Design Requirement (Target) | Successful? | Design Outcome/Specification (Actual) |
|------------------|--|-------------|--|
| Microcontroller | <ul style="list-style-type: none"> - A suitable number of inputs and outputs of which both digital and analogue types must be available (at least one analogue and at least four digital). - A suitable number of timer peripherals must be accessible (at least three timers). - The size and weight of the microcontroller must be minimised for integration with the system such that no significant weight or volume is added to the prototype. | Yes | <p>3.3 V 8 MHz Arduino Pro Mini:</p> <ul style="list-style-type: none"> - Has 14 input/output digital pins (of which 6 can be used as PWM outputs). - Has 6 analogue inputs. - Its dimensions are 33 x 18 mm (compact) and weighs 2 g (lightweight). - Three available timers. |

Table 3.5
Summary of Design Specifications of the Sensory Feedback System.

| System Component | Design Requirement (Target) | Successful? | Design Outcome/Specification (Actual) |
|------------------|--|-------------|---|
| Embodiment | <ul style="list-style-type: none"> - The size and weight of the embodiment of the system must be minimised for integration of the entire system with the prosthetic device such that no significant weight or volume is added to the prosthetic device (hard limit of under 1.29 kilograms, soft limit of under 350 grams). - The embodiment of the system must not hinder or restrict normal operation or function of the prosthetic device (i.e. it must still be able to operate and move as intended with the sensory feedback system attached). | Yes | <p>Custom Design (see Section 3.3.3.2):</p> <ul style="list-style-type: none"> - The entire integrated system (electronic system within the electronic housing, embodiment of the sensors and the embodiment of the feedback mechanism) weighs 172 g <1.29 kg AND <300 g. - The embodiment does not hinder the normal operation or function of the prosthetic device. |

Chapter 4

Design Validation

This chapter outlines the processes followed in validating the design of the sensory feedback system and describes the methodology for the design validation with human participants. Before clinical validation, a Failure Modes and Effects Analysis (FMEA) was conducted on the system. After which the design was taken through two validation processes: waterproof validation and power consumption validation.

The methods and protocols described in this thesis were approved by University of Cape Town's Human Research Ethics Committee (HREC) (reference: HREC REF: 782/2020) and all volunteers signed an informed consent form before participating in and commencing with the study. The approval letter from HREC can be viewed in Appendix [A.6](#).

4.1 Failure Modes and Effects Analysis (FMEA)

An FMEA systematically identifies any risks associated with the device so that the risks can be mitigated accordingly. It enables critical areas of concern to be identified and the weaknesses in the design to be addressed before participant testing. Equation [4.1](#) presents the calculation used to calculate the risk associated with an identified hazard. Table [4.1](#) and [4.2](#) described the severity value and occurrence value (probability) scales, respectively.

$$Risk = Severity Value \times Occurrence Value (Probability) \quad (4.1)$$

The risk evaluation matrix used to evaluate all identified risks is presented in Table [4.3](#). The Risk Analysis and Risk Control tables are presented in Appendix [A.7](#). The necessary safety measures have been applied to all identified hazards to present acceptable residual risks.

4.1. FAILURE MODES AND EFFECTS ANALYSIS (FMEA)

Table 4.1
Severity Value Associated with a Risk.

| Severity Value | Definition | Description |
|----------------|--------------|---|
| 5 | Catastrophic | Potential for great harm or death. Equipment destroyed. |
| 4 | Critical | Results in permanent impairment or life-threatening injury. Significant equipment damage |
| 3 | Major | Results in injury or impairment requiring professional medical intervention. Some equipment or subsystem damage. |
| 2 | Minor | Results in temporary injury or impairment not requiring professional medical intervention. No noticeable performance or equipment damage. |
| 1 | Negligible | Inconvenience or temporary discomfort. Negligible equipment damage. |

Table 4.2
Occurrence Value (Probability) Associated with a Risk.

| Occurrence Value | Definition | Probability |
|------------------|------------|-------------|
| 5 | Frequent | < 1 / 10 |
| 4 | Probable | < 1 / 10 |
| 3 | Occasional | < 1 / 100 |
| 2 | Remote | < 1 / 1000 |
| 1 | Improbable | < 1 / 10000 |

Table 4.3
Risk Evaluation Matrix used to Evaluate Hazards.

| Probability | Severity | | | | |
|-------------|----------|-------|-------|-------|-------|
| | 1 | 2 | 3 | 4 | 5 |
| 1 | ACC | ACC | ACC | ACC* | ACC* |
| 2 | ACC | ACC | ACC* | ACC* | N ACC |
| 3 | ACC | ACC* | ACC* | N ACC | N ACC |
| 4 | ACC* | ACC* | N ACC | N ACC | N ACC |
| 5 | ACC* | N ACC | N ACC | N ACC | N ACC |

Green (ACC) = No control measures required, however they can be implemented if possible.

Orange (ACC*) = Control measure required to minimize the risk to an acceptable level.

Red (N ACC) = Control measure required to eliminate the risk.

4.2 Waterproof Validation

Although the device is not designed to be used in water, the device is designed to be worn in every day life which means there is a possibility that it could be in contact with water at one point or another (rain or accidental spilling, for instance).

Since the sensors are embedded within the 3D printed TPU material, it is important to ensure the sensors are protected from water within this embodiment (i.e. to test that the embodiment is impervious to water). To test this, a piece of tissue paper with an ink dot was placed under the sensor during the embedding process pictured in Figure 4.1. The embodiment with the sensors were then placed under water for one minute, after which the embodiment was cut open to reveal the piece of tissue paper placed under the sensor as pictured in Figure 4.2. The tissue paper was examined for wet spots and compared with a photograph of its original state. This was done for both sensors.

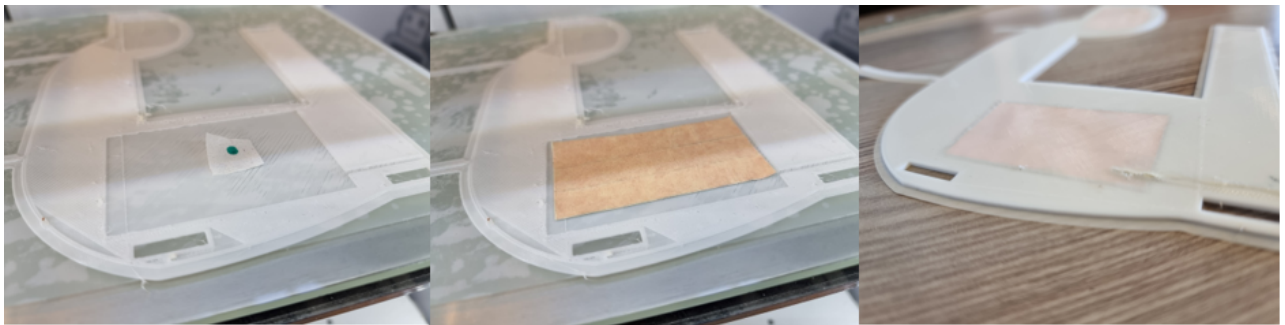


Figure 4.1: Tissue Paper Placement during Embedding Process for Dorsum Sensor.

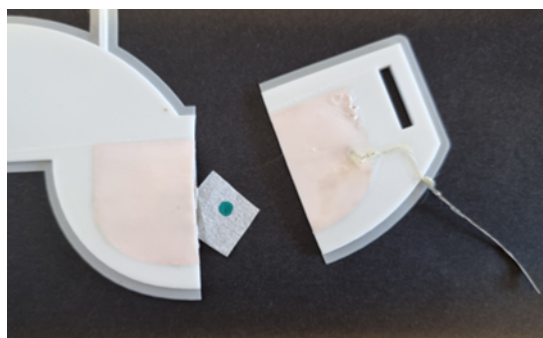


Figure 4.2: Tissue Paper Removal after Water Test.

Figure 4.3 presents the original toilet paper side-by-side with the toilet paper after the embodiment was placed under water for one minute of both sensors. From the figure below, it is evident that the embodiment design is waterproof as there was no evidence of water on or around the tissue paper after the device had been submerged in water for one minute.

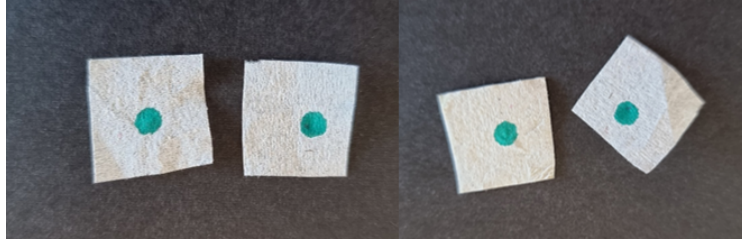


Figure 4.3: Tissue Paper before (Left) Water Test and after (Right).

Further testing to assess how waterproof the electronic enclosure would be required. However, at this stage in the design process it is deemed unnecessary as the design of the electronic enclosure proposed was aimed at neatly enclosing the electronics for testing. It is a preliminary design and will change with further design modifications.

4.3 Power Consumption Validation

The power consumption of the device was calculated in Chapter 5.10(c) Section 3.3.2.2. To validate these calculations, a simulated use experiment was conducted where the device was used on the body powered prosthesis by the author for one day (awake cycle of 18 hours). Before commencing, the battery was fully charged. Throughout the day of use, the author made use of the devices (the body powered prosthesis and the sensory feedback system) just as a transradial amputee would make use of the devices ensuring that the sensors and vibration motor discs were activated sufficiently to simulate an accurate use-case. The battery, fully charged at the beginning of the day, was able to supply power for the entire awake cycle of 18 hours. Furthermore, without re-charging the battery overnight, the device was still able to operate the next day indicating that the battery has capacity to power the system for longer than 18 hours. Thus, the choice of battery capacity was validated and this proved that the calculations presented in Section 3.3.2.2 were accurate.

4.4 Participant Testing

To evaluate if the feedback provided by the device is effective when the prosthesis is being moved autonomously and to evaluate all the sensors in a holistic manner, an object identification and size discrimination (OISD) test was conducted simultaneously.

To evaluate the efficacy of the capacitive sensors in relaying information about proximity and touch, an object identification test was conducted. To evaluate the efficacy of the flex sensor in relaying proprioceptive information about the position and motion of the fingers of the prosthetic device, an object size discrimination test was conducted. The two tests were simultaneously conducted: the participant first had to identify if there was an object present and then determine its size relative to another object.

4.4.1 Test Participants

Five able-bodied, adult volunteers (four men and one woman; mean age of 28.6 ± 4.83 years and mean upper arm diameter of 23.1 ± 1.75 cm [*mean \pm standard deviation*]) participated in a study conducted at the Medical Devices Lab at the University of Cape Town. None of the volunteers had previous experience with the sensory feedback system, and all but one had limited to no experience with the modified body powered prosthesis used to test the sensory feedback system. One volunteer's experience with the body powered prosthesis is considered extensive. This participant was used as an example of someone with prior experience in the use of the prosthetic device.

Three participants were right-hand dominant (two were left-hand dominant). None of the volunteers had any known sensory, cognitive or skin problems, nor had any other disability that could impede their ability to follow instructions, nor had any pathology that could affect tactile or proprioceptive sensibility, or muscular activity of any kind. Written informed consent was obtained from each participant before commencement of testing.

4.4.2 Experimental Setup

A 3-object, forced choice OISD test was administered to each participant to assess the effect of the sensory feedback system on OISD performance. Forced implies that the objects were presented to the participant instead of the participant searching for the objects themselves. During each test, participants were blindfolded and given noise-cancelling headphones (Sony WH-1000XM3) playing pink noise. Removing auditory input prevents the participant from hearing the vibration of the motor discs on the feedback mechanism. Removing visual assistance prevented participants from relying on constant visual attention of the object and to prevent the participant from seeing the sizes of the objects instead of being able to distinguish them from the feedback received from the system. This acts as a control measure.

4.4. PARTICIPANT TESTING

For the purposes of this test, metal spheres were used. The chosen spheres are presented in Figure 4.4 and can be characterised according to their diameter size as follows: 3.5 cm (small), 5 cm (medium) and 9 cm (large). The diameter of each sphere is greater than the Just Noticeable Difference (JND) relative to the other spheres. The JND is the smallest change in volume that a person is able to sense or notice. The chosen spheres are significantly different in diameter size so much so that a person would be able to tell the difference amongst them by looking at the spheres or examining them with their hands provided there was nothing wrong with their sensation.



Figure 4.4: Metal Spheres used for Testing (Left to Right: Large, Medium and Small).

The upper arm diameter of each participant was measured and the haptic motors were adjusted accordingly to ensure that the three haptics were spaced proportionally. Figure 4.5 presents how the haptic motors were placed. The haptic linked to the palmar capacitive sensor was placed on the anterior surface, the haptic linked to the dorsum capacitive sensor was placed on the posterior surface and the haptic linked to the flex sensor was placed on the medial surface.

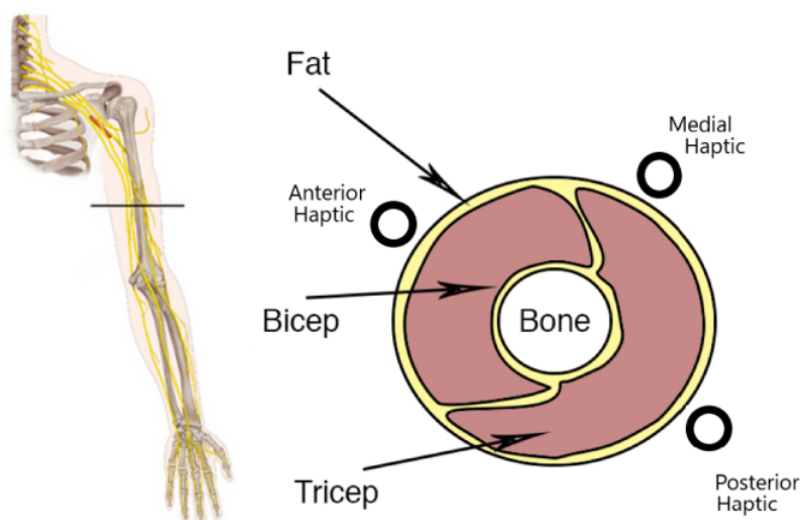


Figure 4.5: Placement of Haptics on Participants (Image Adapted from Clinical Gate (2021)).

4.4.3 Functional Tests

The orientation of the prosthetic hand when presented with the objects was positioned such that the palm of the hand pointed upwards towards the ceiling. The participants were not informed when an object was presented to them. They were told to grip the object when they believed there was an object available to grip (i.e. only grip if the feedback from the capacitive sensors indicated that there was an object present). This was the object identification portion of the test. During testing, the participant was presented with a pair of spheres at a time for each trial and asked to tell whether the first sphere presented to them was smaller, equal to or larger in size to the second sphere based on the feedback they received from the device. This was the object size discrimination portion of the test.

For each trial, participants were asked to rate their confidence, on a scale of 0% to 100%, in their ability to accurately identify and discriminate amongst the presented spheres. Three response times were recorded for each trial: one to record the time taken to identify sphere 1 (S1), one to record the time taken to identify sphere 2 (S2) and lastly, one to record the time taken to discriminate between the sizes of the two spheres. This is to evaluate the learnability of the device: does participant performance improve the longer they use the device?

Each test per participant lasted approximately 1 hour. Participants were presented with six different variations of pairs of spheres and were asked to determine whether the first sphere was smaller than, equal to or bigger than the second sphere. Each pair of spheres was presented twice (one with the first element being presented first and another one with the first element presented as second) for a total of twelve trials. The trial was conducted under two conditions: (1) without the sensory feedback and (2) with the sensory feedback. Thus, each participant completed a total of 24 trials.

4.4.4 Procedure

The procedure outlined below was followed during participant testing:

1. Participant was given the informed consent document and the moderator guided them through the procedure. Once the informed consent form was signed, the test could begin.
2. A measurement of the participant upper arm diameter was taken and the haptic enclosures were equally spaced accordingly for each participant.

3. The haptic motor linked to the palmar capacitive sensor was placed on the anterior surface of the upper arm, the flex sensor haptic was placed on the medial surface of the upper arm and the haptic linked to the dorsum was placed on the posterior surface of the upper arm for all participants.
4. Initially, the participant was given the prosthetic device on its own to allow them to become familiar with the device. Once the participant felt confident in the operation of the device, they were asked to complete the following task to prove competency:
 - Pick up five different objects, one at a time, from a box at one end of a table and place them in a box on the other side of the table.
5. Once competency was recorded, the sensory feedback system was applied to the prosthetic device. The moderator explained the basic workings of the device and demonstrated how it works. This allowed the participant to become familiar with the different locations of the vibration and the various vibration intensities and established what they all mean.
6. The participant was asked again to complete the task described in point 2. Once successfully completed, the actual test could begin.
7. The participant was given instructions as to how the test would be administered: they would be blindfolded and wearing noise cancelling headphones. The sensory feedback system would be turned OFF for the first group of tests and turned ON for the last group of tests. They would not be informed when an object was required to be gripped - they were to grip when they believed there was an object present.
8. The orientation of the prosthetic hand when presented with the objects was to be positioned such that the palm of the hand points upwards towards the ceiling.
9. For the condition of no sensory feedback, participants were informed by a tap on their non-dominant hand when an object was presented to them. For the condition of sensory feedback, participants were not informed and had to grip when they “sensed” the object was present.
10. Various arrangements of object sizes were presented to the participants, and were asked to say whether the first sphere was smaller, equal to or larger than the second sphere.
11. Results were recorded in Table 4.4.

Figure 4.6 and 4.7 present images of the sensory feedback system during testing with a participant.

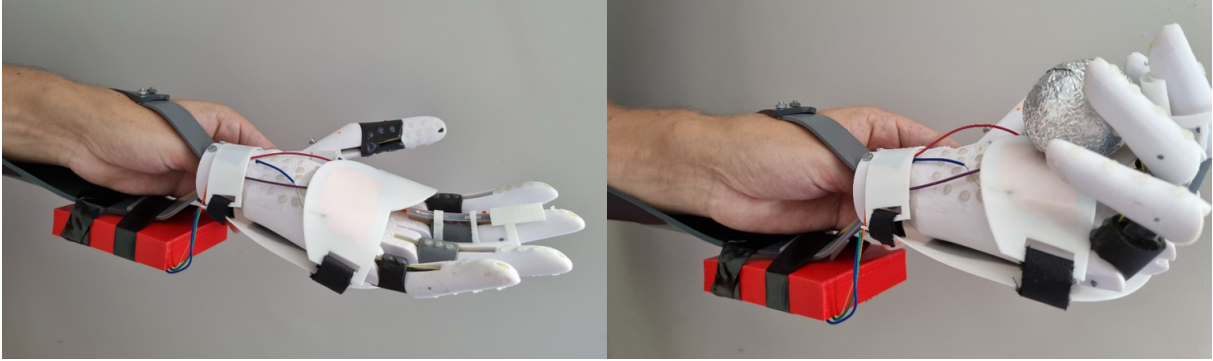


Figure 4.6: Sensory Feedback System on Participant (Left: Fully Extended, Right: Fully Flexed Grasping a Sphere).

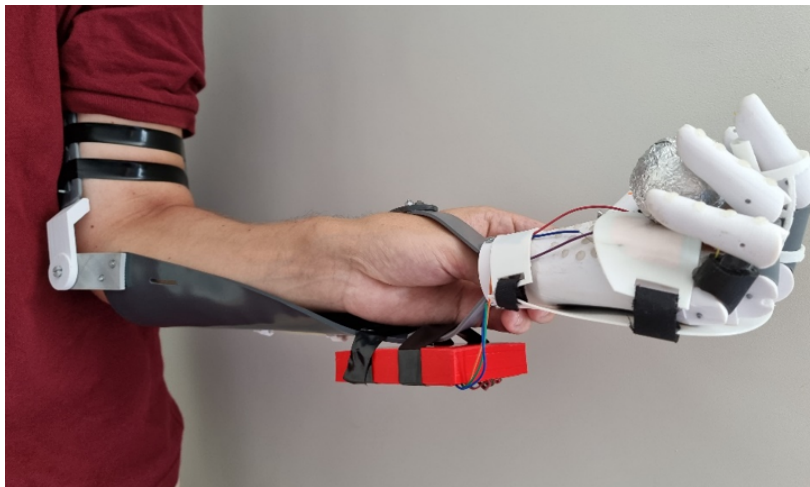


Figure 4.7: Sensory Feedback System on Participant Grasping a Sphere.

4.4.5 Scoring System

Table 4.4 illustrates how the raw data from testing was recorded. S refers to the small sphere, M the medium sphere and L the large sphere.

Table 4.4

Scoring Template for Each Participant (Repeated for a Sensory Feedback System and No Sensory Feedback System).

| Trial No. | Comparison (S1 vs S2) | Object Identification S1 | Response Time (s) | Object Identification S2 | Response Time (s) | Size Discrimination (S1 >, =, <S2) | Response Time (s) | Confidence (%) |
|-----------|-----------------------|--------------------------|-------------------|--------------------------|-------------------|------------------------------------|-------------------|----------------|
| 1 | S vs M | | | | | | | |
| 2 | M vs S | | | | | | | |
| 3 | S vs S | | | | | | | |
| 4 | S vs S | | | | | | | |
| 5 | S vs L | | | | | | | |
| 6 | L vs S | | | | | | | |
| 7 | M vs M | | | | | | | |
| 8 | M vs M | | | | | | | |
| 9 | M vs L | | | | | | | |
| 10 | L vs M | | | | | | | |
| 11 | L vs L | | | | | | | |
| 12 | L vs L | | | | | | | |

The object identification (S1 and S2) tasks were scored a 1, 0.5 or 0. A score of 1 indicates correct execution of the task (correctly identified the presence of object and at the correct sensor location), a score of 0.5 indicates that they identified the presence of an object but at the wrong sensor location and a score of 0 indicates failure to identify the presence of object at all. Size discrimination tasks were scored a 1 or 0. A score of 1 indicates that the size discrimination task was executed with success, while a 0 indicates failure to correctly discriminate the size between the two spheres. Confidence is a subjective rating given by the participant. The participant was told to rate their confidence in their answer for size discrimination between 0 and 100% and therefore, it is scored between 0 and 100%. Average accuracy scores (means) will be calculated and used to analyse the results.

Chapter 5

Results and Analysis of Results

This chapter presents the results and analysis of results from participant testing, as presented and described in Section 4.4, for the purpose of design validation of the sensory feedback system presented and described in Section 3. The raw data from testing can be viewed in Appendix A.8.

5.1 Objection Identification

Object identification was tested as follows: participants were instructed only to flex the hand of the prosthesis when an object was presented to them at the palm location. Objects were presented to participants by hovering the object above the palm or dorsum of the hand (approximately between 2 and 4 cm away).

All participants performed best when the sensory feedback system was active and most poorly when no sensory feedback was provided. All five participants received an average accuracy score of 0% for object identification when there was no sensory feedback as no participant was able to identify that an object had been presented to them. When the sensory feedback system was active, all five participants were able to correctly identify all objects (i.e. the three metal spheres varying in size) presented to them, and at the correct location, at an average accuracy of 100%. Therefore, there was a 100% increase in average accuracy for all participants between conditions of no sensory feedback and sensory feedback.

Furthermore, the response time (the time taken to identify an object presented) improved over time for each participant when sensory feedback was active. Figure 5.2 and 5.1 present the graphical illustrations of the improvement (seen as a reduction over time) in response time for each participant. This improvement is shown by a significantly negative relationship in the trend lines between response time and progression through the test (the response time for object identification decreased as the participant progressed through the test indicating a learnability with the sensory feedback system: the more it was used, the quicker and more cognitive the participant was in recognising that there was an object presented to them). Figure 5.3 presents the average response time for all participants as a function of trial number (0 to 12). The figure illustrates an average negative correlation in response time for all participants as they progressed from the beginning to the end of the trial. The negative relationship is highlighted by the negative gradient of all trend lines of the linear functions.

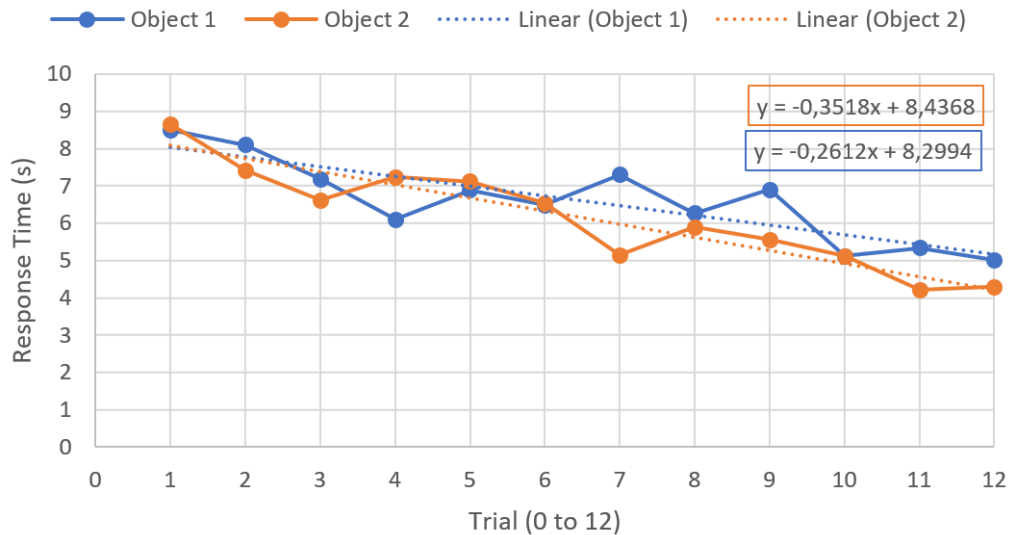
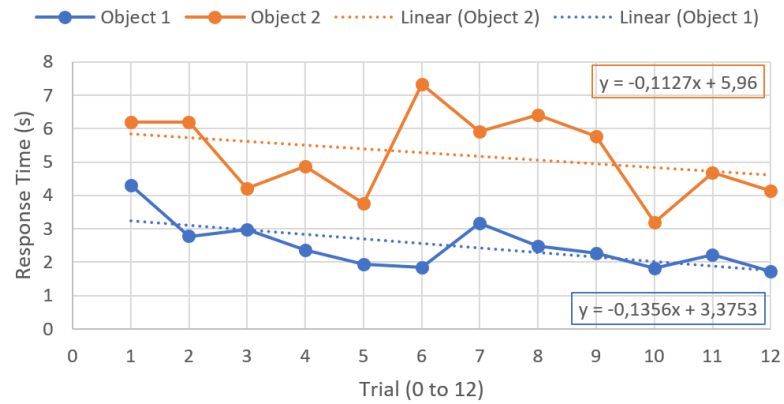
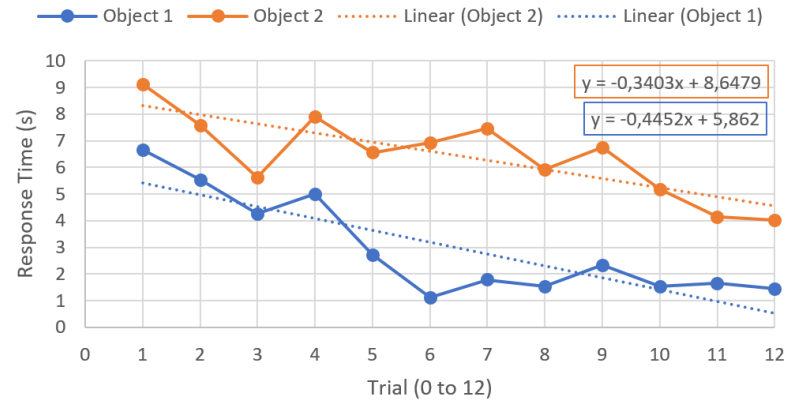


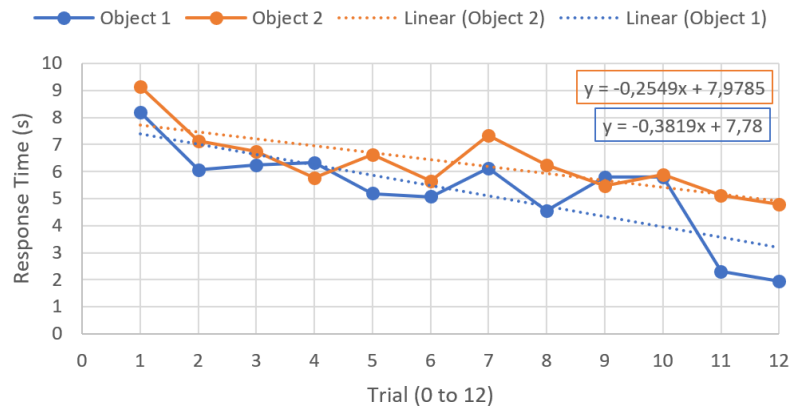
Figure 5.1: Response Time as a Function of Trial Number (0 to 12) for Participant 5.



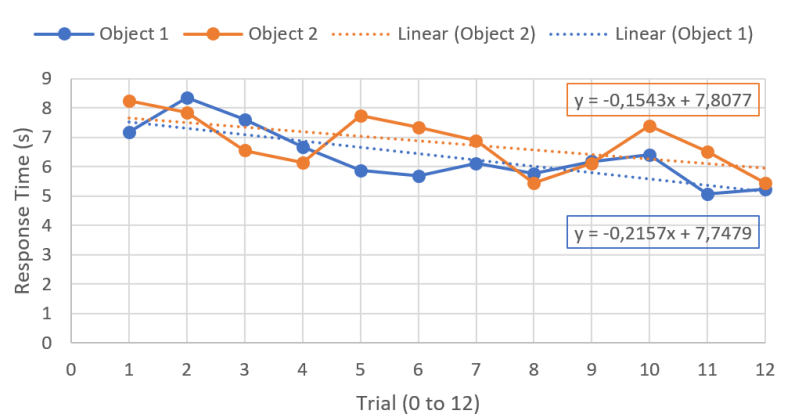
(a) Participant 1.



(b) Participant 2.



(c) Participant 3.



(d) Participant 4.

Figure 5.2: Response Time as a Function of Trial Number (0 to 12) for Participant 1 to 4.

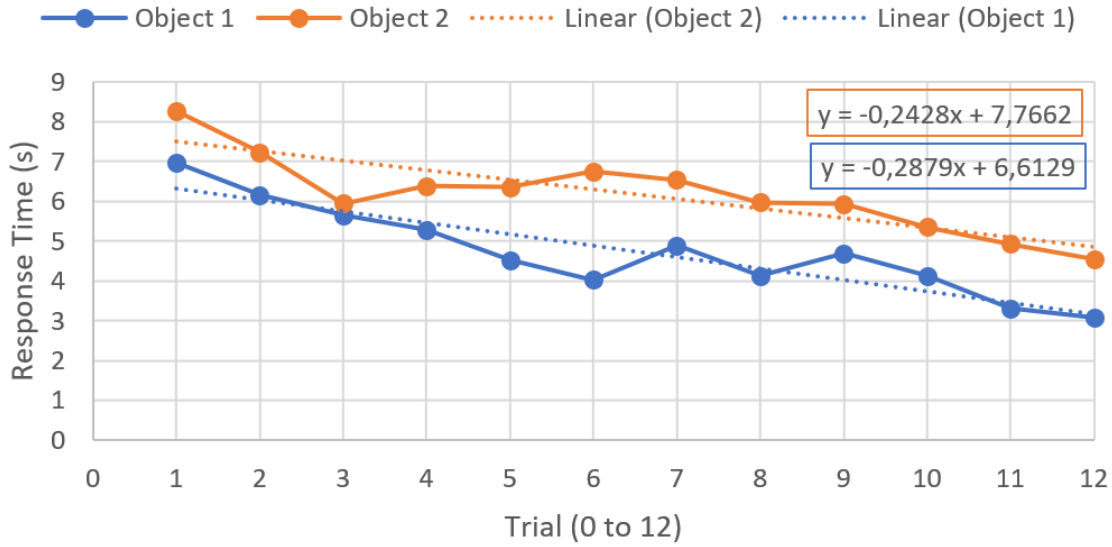


Figure 5.3: Average Response Time for All Participants as a Function of Trial Number (0 to 12).

5.2 Object Size Discrimination

Figure 5.4 and 5.5 present comparisons of each participant’s accuracy in size discrimination tasks with no sensory feedback and with sensory feedback, respectively. It is evident from the figures that participants were able to accurately discriminate between sphere sizes better when there was sensory feedback as opposed to when there was no sensory feedback.

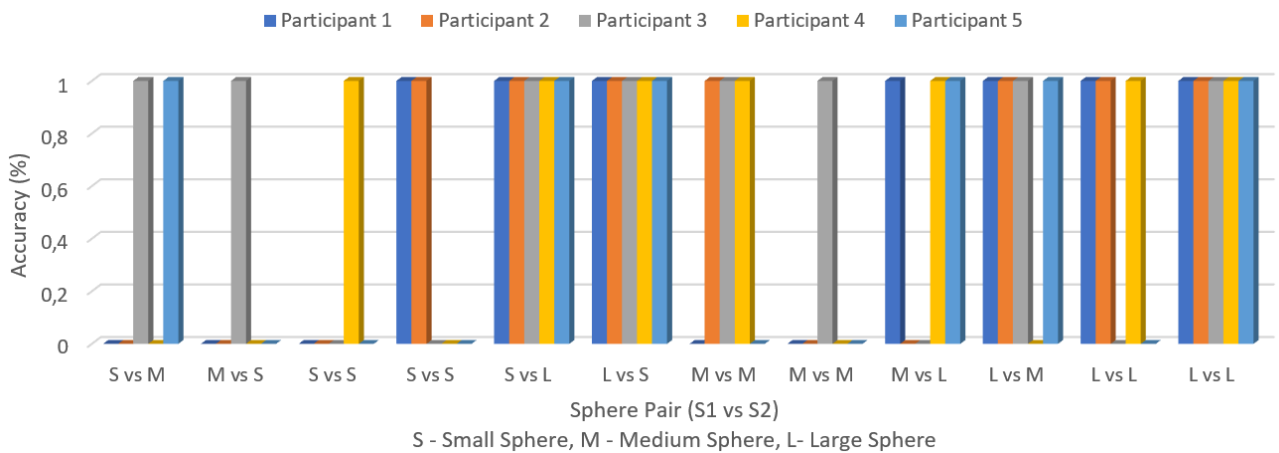


Figure 5.4: Comparison of Participant Accuracy in Size Discrimination Tasks (No Sensory Feedback).

5.2. OBJECT SIZE DISCRIMINATION

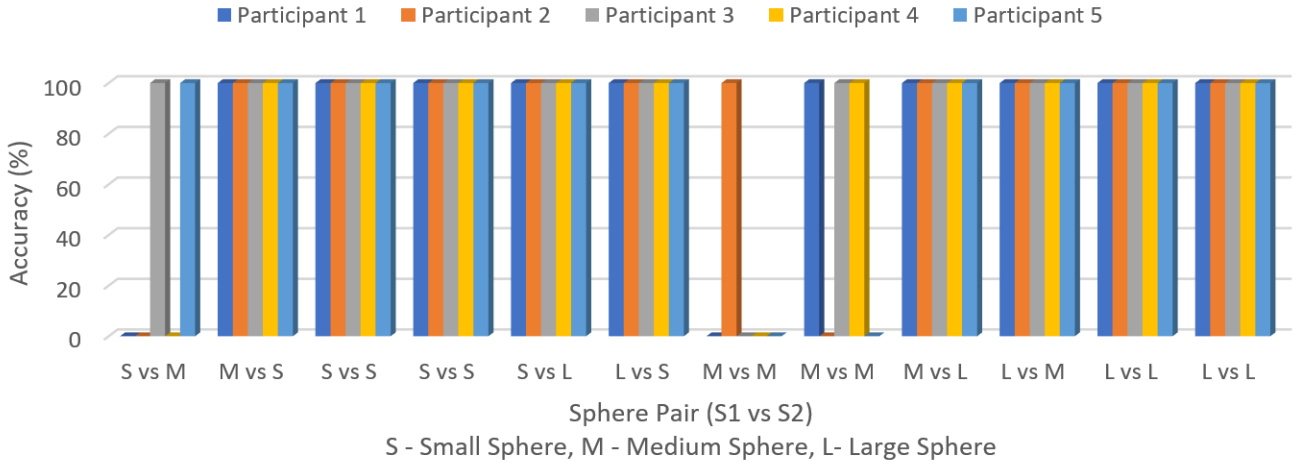


Figure 5.5: Comparison of Participant Accuracy in Size Discrimination Tasks (Sensory Feedback).

Figure 5.6 presents a comparison of average participant accuracy in all size discrimination tasks for no sensory feedback and sensory feedback. Figure 5.7 presents a comparison of average participant accuracy in size discrimination arrangements (i.e. S vs M and M vs S are taken as one arrangement) for no sensory feedback and sensory feedback.

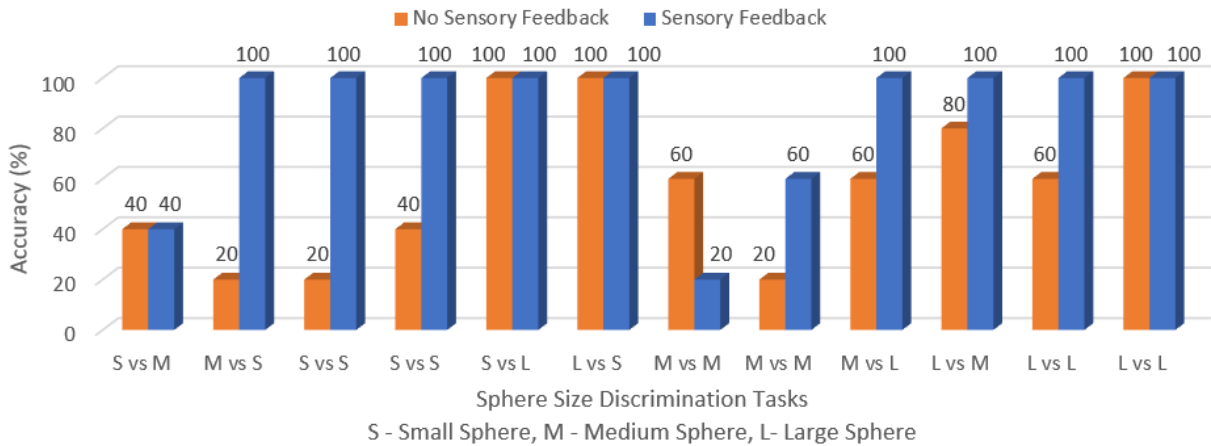


Figure 5.6: Comparison of Average Participant Accuracy in All Size Discrimination Tasks for Different Conditions.

5.2. OBJECT SIZE DISCRIMINATION

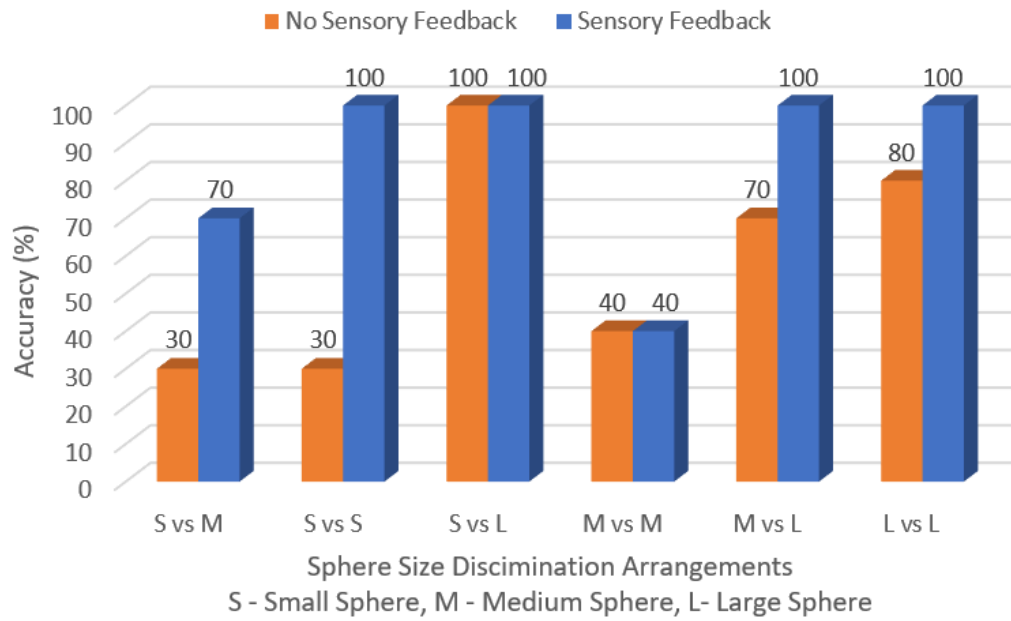


Figure 5.7: Comparison of Average Participant Accuracy in Size Discrimination Tasks for Different Conditions.

From Figure 5.7, it is evident that on average participant accuracy improved or stayed the same when sensory feedback was activated. The accuracy of the performance of participants improved with four out of the six arrangements (i.e. improved in 66.67% of the arrangements) when sensory feedback was provided and stayed the same for two of the six arrangements (i.e. stayed the same in 33.33% of arrangements). This is an indication that providing sensory feedback did not worsen results and on average improved them.

5.2. OBJECT SIZE DISCRIMINATION

When differentiating between spheres classified as “small” and “large” and all arrangements associated with them (S vs S, S vs L, L vs L), participants discriminated against the pairs at an average accuracy of 100% with sensory feedback. This indicates that due to the larger size difference between the two spheres (a difference of 5.5 cm in diameter), the sensory feedback system was able to accurately relay information to the user about the variation in size (the haptic discs vibrated at 100% intensity for the “small” sphere and 31% intensity for the “large” sphere).

When adding the “medium” sphere into the discriminating tasks, participants were on average able to accurately discriminate between the “medium” and “large” sphere 100% of the time; however they were only able to discriminate between the “small” and “medium” sphere 70% of the time. There is a 1.5 cm difference in diameter between the “small” and “medium” sphere, and a 4 cm difference in diameter between the “medium” and “large” sphere. The haptics vibrated at 50% intensity for the “medium” sphere but owing to the small difference in diameter size between the “small” and “medium” spheres; the sensory feedback system is not as accurate at relaying the information to the user suggesting that the range of vibration in the code of the microcontroller needs to be improved upon. The larger diameter difference between the “medium” and “large” sphere made it easier for the sensory feedback system to relay accurate information to the user.

An important note to mention is that although on average the sensory feedback and no sensory feedback did not improve results for “medium” sphere discrimination for equal size; Figure 5.6 illustrates that when sensory feedback was active, participants improved at identifying if the “medium” spheres were equal between sphere size tasks (from 20% to 60%) whereas no sensory feedback proved to worsen the discrimination of “medium” spheres as equal (from 60% to 20%). The same analysis can be said for S vs M and M vs S, where the participants improved from 40% to 100% as opposed to for no sensory feedback where results worsened from 40% to 20%.

Both conditions of feedback had difficulty with the “medium” sphere when it came to being presented equal sizes of the sphere. This could be due to its diameter being too close to the diameter of the “small” sphere illustrating that further distinct calibration of the system is required.

Figure 5.8 illustrates the difference in average accuracy amongst all participants when completing size discrimination tasks with no sensory feedback and with sensory feedback. As presented in the figure, the accuracy values are significantly lower when no sensory feedback is applied compared to when sensory feedback is active. The accuracy values range between 50% to 66.67% (a difference of 16.67%) for no sensory feedback as opposed

to ranging between 83.33% to 91.67% (a difference of 8.34%) for sensory feedback. The median accuracy value for the five participants was 58.33% without sensory feedback and 85% with sensory feedback. Furthermore, Figure 5.8 illustrates that the data is more dispersed for no sensory feedback versus with sensory feedback. This indicates that the accuracy with sensory feedback active is more likely to fall closer around the median of 85% (with a standard deviation of 8.34%) versus no sensory feedback where it is more likely to be more dispersed from the median of 58.33% (with a standard deviation of 16.67%).

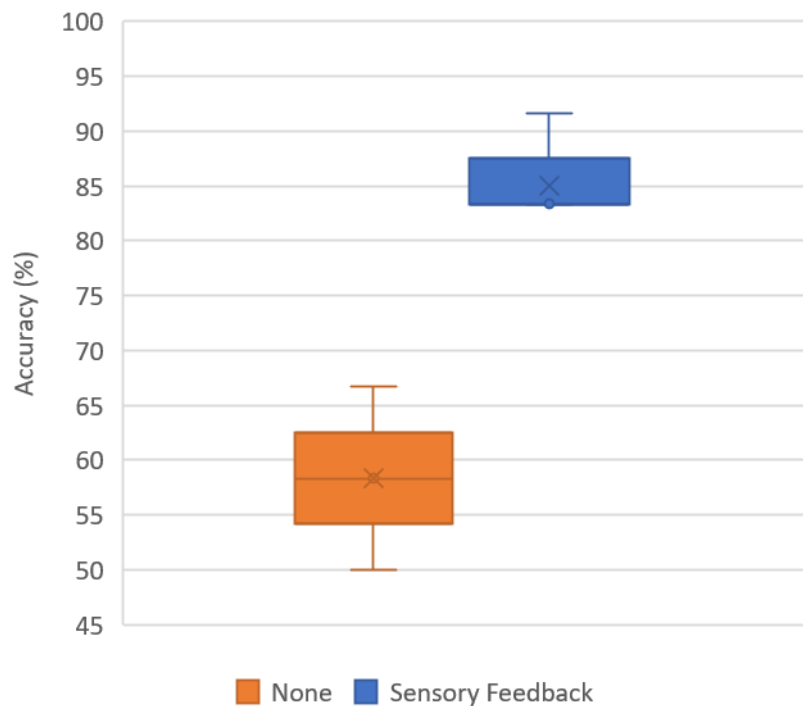


Figure 5.8: Comparison of Participant Average Accuracy in Size Discrimination.

Artificial sensory feedback significantly improved size discrimination accuracy in all participants. The sensory feedback system demonstrated an improvement in size discrimination across all arrangements but on average the “medium” sphere was the most difficult to discriminate against for equal size tasks. However, participants were able to distinguish on average between “medium” spheres when paired with the “large” (at 100% accuracy) or “small” sphere (at 70% accuracy).

Furthermore, the response time (the time taken to discriminate between spheres) improved over time for each participant when sensory feedback was active. Figure 5.9 presents the average response time for all participants for size discrimination as a function of trial number (0 to 12). The figure illustrates an average negative relationship in response time for all participants as they progressed from the beginning to the end of the trial.

5.2. OBJECT SIZE DISCRIMINATION

Figure 5.10 and 5.11 present the graphical illustrations of the improvement (seen as a reduction over time) in response time for each participant. This improvement is shown by a significantly negative relationship in the trend lines between response time and progression through the test (the response time for object identification decreased as the participant progressed through the test indicating a learnability with the sensory feedback system: the more it was used, the quicker and more cognitive the participant was in determining the size of the spheres accurately).

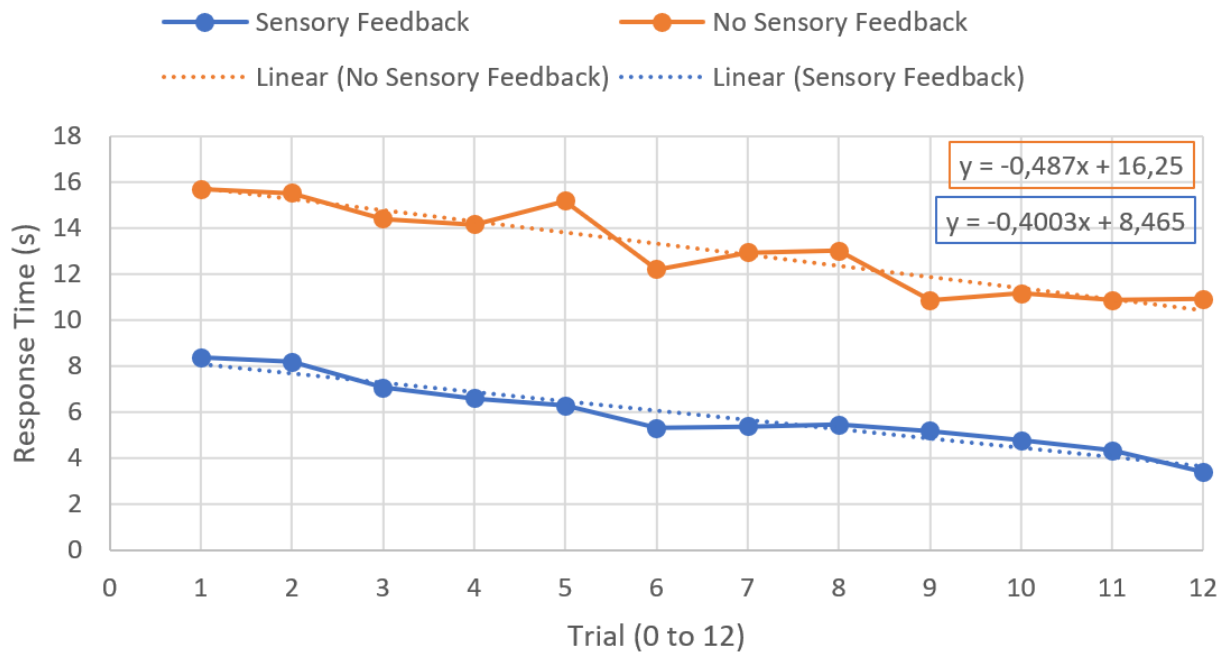
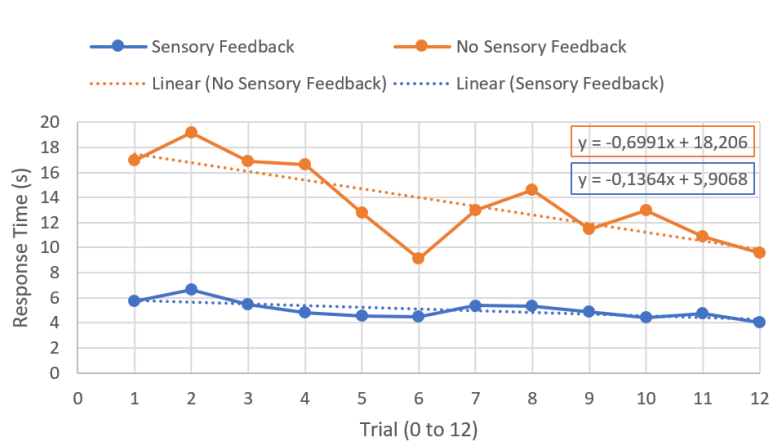
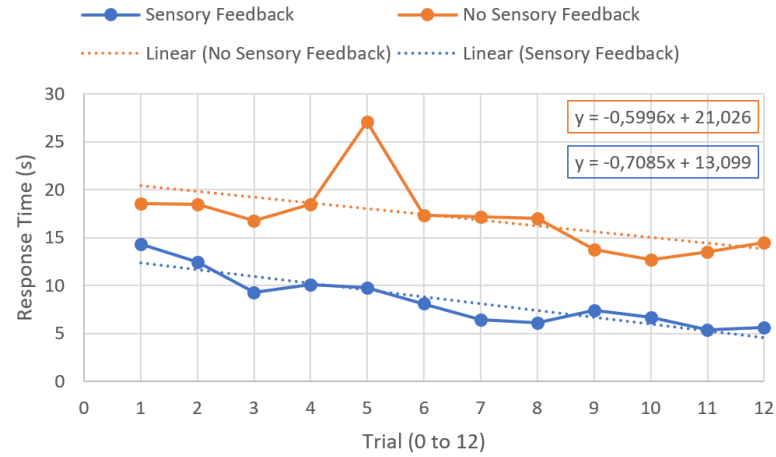


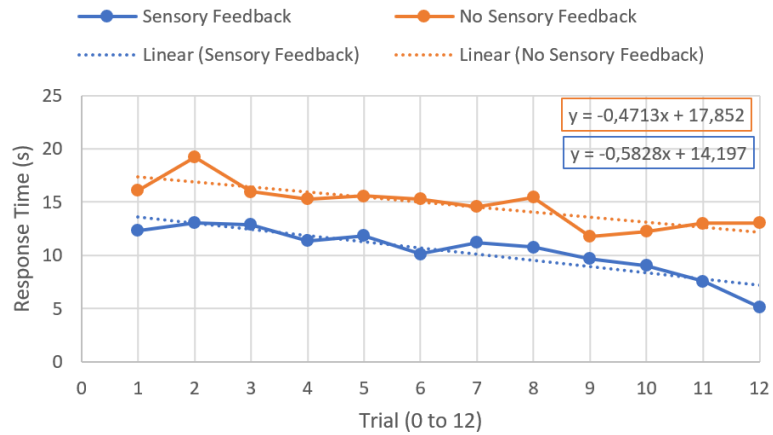
Figure 5.9: Average Response Time for All Participants for Size Discrimination as a Function of Trial Number (0 to 12).



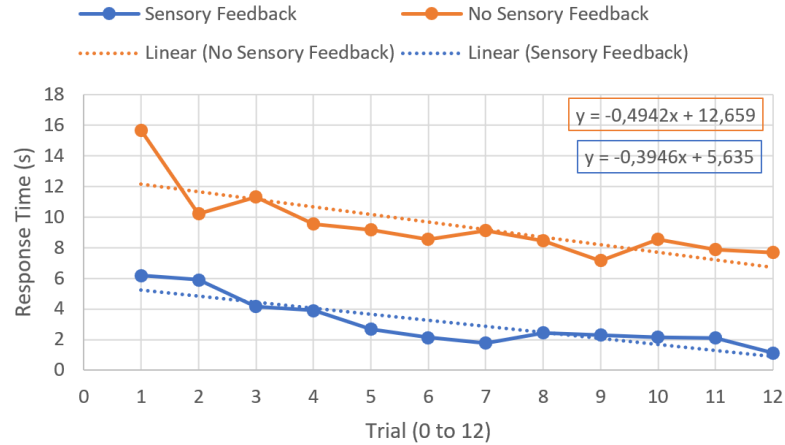
(a) Participant 1.



(b) Participant 2.



(c) Participant 3.



(d) Participant 4.

Figure 5.10: Response Time for Size Discrimination as a Function of Trial Number (0 to 12) for Participant 1 to 4.

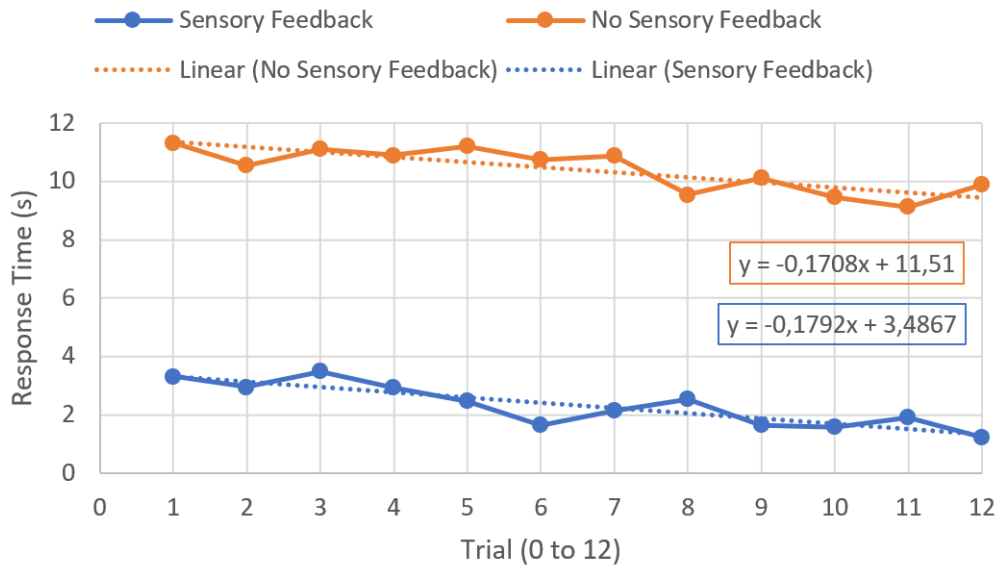


Figure 5.11: Response Time for Size Discrimination as a Function of Trial Number (0 to 12) for Participant 5.

5.3 Participant Confidence

All five participants were more confident in performing the tasks with sensory feedback active than with no sensory feedback. Figure 5.12 presents a comparison graph to illustrate the difference in average participant confidence levels as a function of feedback. From the graph, it is evident that perceived confidence increased with addition of feedback.

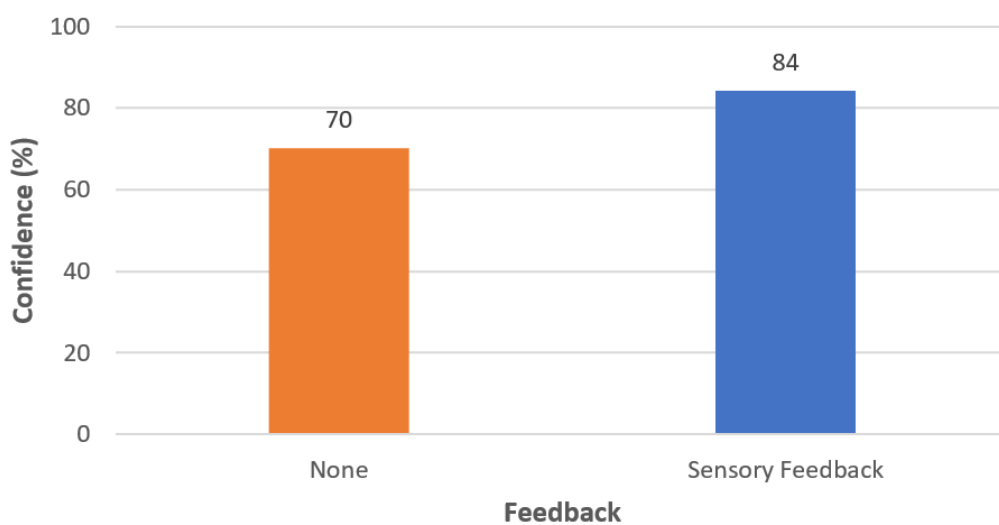


Figure 5.12: Average Confidence Levels for All Participants for Size Discrimination Tasks as a Function of Feedback.

5.3. PARTICIPANT CONFIDENCE

Figure 5.14 illustrates the significant positive correlation (seen as positive gradient trend lines) between each participant’s confidence as the trial progressed from trial 0 to 12. Figure 5.13 illustrates the significant positive correlation (seen as a positive gradient trend line) between participant confidence and participant accuracy in size discrimination even though the participants were not aware of the results. Participants were on average less confident in their answers and less accurate with their answers with no sensory feedback than with sensory feedback. It is evident that participants tended to underestimate actual performance. As presented in Figure 5.15 on average, confidence and accuracy was higher for sensory feedback versus no sensory feedback when the participants were presented with spheres of “small” or “large” sizes, and lowest when presented with “medium” spheres paired with “small” or “medium” spheres; however, sensory feedback on average performed better in 92% of the tasks (11 out of 12) than no sensory feedback.

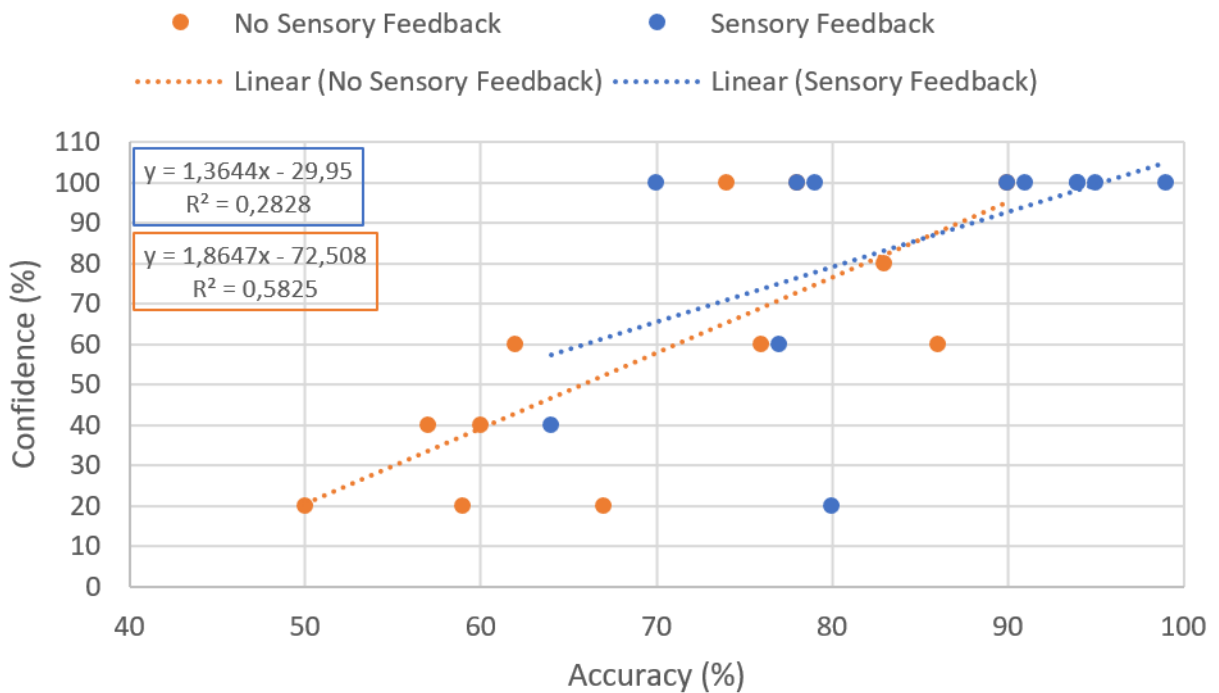


Figure 5.13: Average Confidence Levels of All Participants for Size Discrimination as a Function of Average Accuracy for Sensory Feedback (Blue) and No Sensory Feedback (Orange).

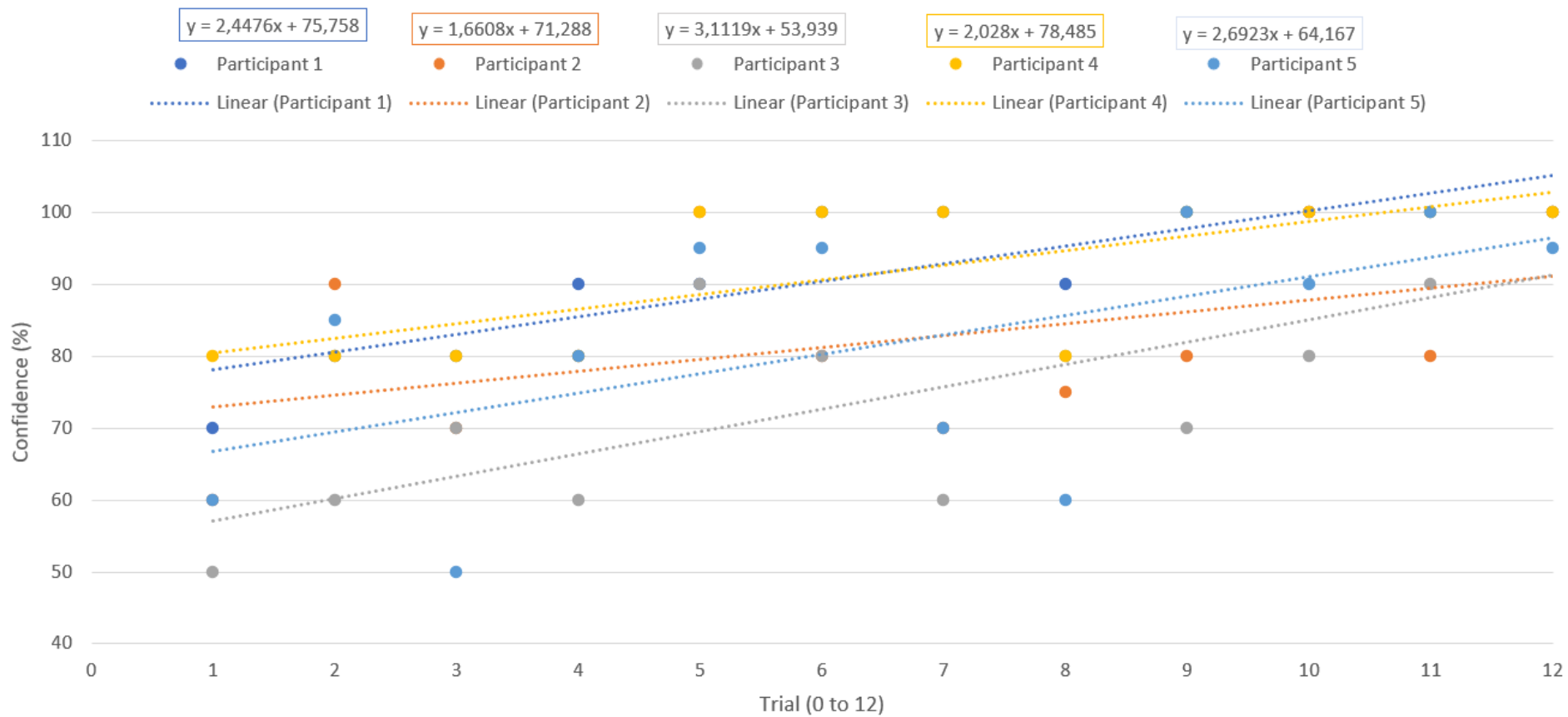


Figure 5.14: Average Confidence Levels for Each Participant for Size Discrimination Tasks with Sensory Feedback.

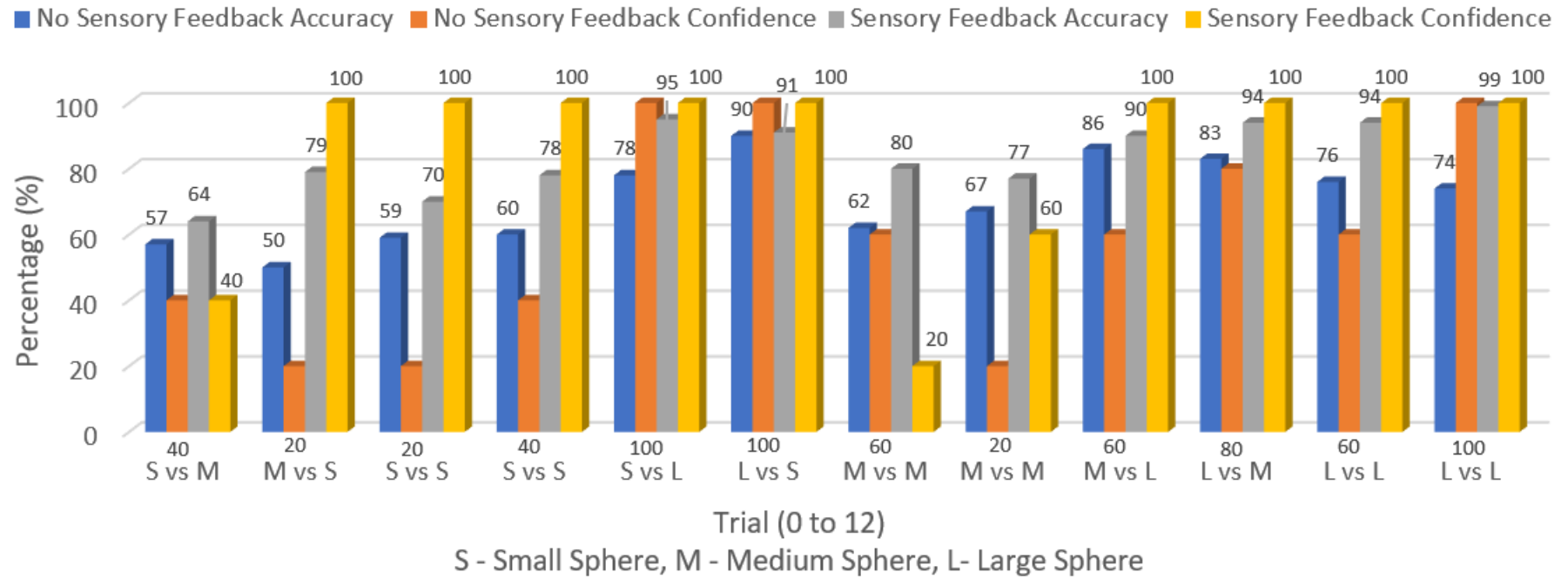


Figure 5.15: Average Confidence Levels and Average Accuracy Levels of All Participants as a Function of Size Discrimination Arrangement.

Chapter 6

Conclusions

In this thesis, the effects of tactile and proprioceptive feedback on object identification and size discrimination (OISD) tasks were investigated. The design, development and testing of a non-invasive sensory feedback system that mediates detection of touch and proximity, and mediates detection of the position and motion of the fingers by relaying information to the user in the form of a vibrotactile upper armband were described in detail. All participants performed comparably during the design validation of the device.

This project aimed to develop a non-invasive sensory feedback system, including proprioceptive feedback, to work in conjunction with an existing body powered prosthesis that provided the user with increased tactile and proprioceptive awareness demonstrated in the form of improved results in an object identification and size discrimination (OISD) test, improved results in confidence levels and improved results in response time.

6.1 Design

In Section 3.3.6 Table 3.5, the design was evaluated against the design requirements outlined in Chapter 3 to form a design specification for the system. This design specification outlined the specifications for the designed sensory feedback system and illustrated how the design requirements for the device were met.

Table 3.5 illustrated that all design requirements were met with success pending the evaluation of one requirement under the feedback mechanism:

- The feedback system is to provide the user with increased tactile and proprioceptive awareness demonstrated by improved results in an object identification and size discrimination (OISD) test, improved results in confidence levels and improved response times.

This design requirement was evaluated in participant testing. A summary of the results are described below.

6.2 Design Validation

6.2.1 Sensory Feedback Improves Object Identification Accuracy

All five participants could identify objects most accurately and efficiently when sensory feedback was provided in the form of a vibration sensation on the upper arm which increased in intensity as the object moved closer to the sensor. All participants performed worst when no sensory feedback was provided. There was a 100% improvement for object identification accuracy between no sensory feedback and sensory feedback.

6.2.2 Sensory Feedback Improves Object Size Discrimination Accuracy

Three spheres of various diameters were presented to participants in pairs, and presented twice for each trial. Once with the first sphere presented before the second sphere and second, with the first sphere presented after the second sphere. The diameter of the spheres and their name classification was as follows: 3.5 cm (small), 5 cm (medium) and 9 cm (large).

All five participants could discriminate the sizes of objects most accurately and efficiently when sensory feedback was provided in the form of a vibration sensation on the upper arm which decreased in intensity as the fingers of the prosthesis flexed (lowest intensity vibration at the beginning of flexion and highest intensity at the end of flexion). All participants performed worst when no sensory feedback was provided. Object size discrimination accuracy improved from a mean accuracy of 58.33% without sensory feedback to 85% with sensory feedback.

All five participants could discriminate between “large” and “small” spheres and all possible arrangements (S vs S, L vs L, S vs L, L vs S) 100% of the time for all arrangements. All participants could also discriminate between “medium” and “large” spheres 100% of the time for the following arrangements: M vs L, and L vs M. The large difference in the diameters of “small” and “large” spheres (5.5 cm difference) and “medium” and “large” spheres (4 cm difference) and the accuracy with which participants were able to distinguish amongst them suggests that the sensory feedback system is able to accurately relay information to the user about the variations in size of these spheres.

For tasks where the participant was required to recognise equal sizes of the “medium” spheres, the sensory feedback improved results from 20% to 60%, whilst no sensory feedback worsened the results from 60% to 20%. For tasks where the participant was required to recognise the difference between the “small” and “medium” spheres, sensory feedback improved the results from 40% to 100% whilst no sensory feedback worsened results from 40% to 20%. The small difference in diameter size between the “small” and “medium” spheres (1.5 cm difference) indicates that the sensory feedback system has difficulty relaying accurate information to the user which suggests further distinct calibration of the system is required for S vs M and M vs M arrangements.

The overall results from the object size discrimination task illustrates the potential for improving object identification and recognition by adding sensory feedback to prosthetic devices.

6.2.3 Sensory Feedback Reduces Response Time in Execution of Tasks

Providing sensory feedback improved the response time to identify an object and to discriminate its size. This improvement was seen in a reduction in response time over the period of testing indicated by a significant negative relationship (negative gradient) in the trend lines for response time as a function of trial (0 to 12) for both object identification tasks and size discrimination tasks. This illustrates a dimension of learnability of the device: the more the device is used; the more cognisant the participant becomes with the device and the better their performance is in accuracy and response time. This demonstrates the potential for improving object size discrimination and recognition by adding sensory feedback to prosthetic devices.

6.2.4 Sensory Feedback Improves Participant Confidence Levels

Confidence levels for size discrimination tasks were highest when sensory feedback was active. There was a significant positive correlation between accuracy and confidence (illustrated by positive gradient trend lines). Without sensory feedback, confidence was on average 70%, but increased to 84% when provided with sensory feedback. There is a chance that participants had response bias (purposefully misreported or misrepresented their confidence based on what they thought the moderator wanted to hear); however, the confidence was also notably correlated with accuracy in size discrimination tasks even though participants received no indication of results. Therefore, unless the participant deliberately gave wrong answers without sensory feedback; it is evident that the data indicates an improved perception of capability in their use of the prosthetic arm. Due to the learnability of the device, confidence levels are expected to further increase as the user becomes more cognisant during use and with the addition of visual confirmation.

6.2.5 Overall Outcome

All design requirements outlined in Chapter 3 for the sensory feedback system were successfully met and the aim of this project was successfully achieved: to develop a non-invasive sensory feedback system, including proprioceptive feedback, to work in conjunction with an existing body powered prosthesis that provides the user with increased tactile and proprioceptive awareness demonstrated in the form of improved results in an object identification and size discrimination (OISD) test, improved confidence levels and improved results in response time.

This thesis demonstrated that the design and development of a sensory feedback system that added artificial somatosensation (sensory feedback) was successful in improving OISD accuracy, improving confident levels and reducing response time in execution of tasks.

Chapter 7

Recommendations and Future Work

7.1 Design Recommendations

The first prototype of the sensory feedback system designed and developed can be considered a viable proof-of-concept model of the device based on the results and analysis of results from preliminary testing presented in Section 5; however, minor deficiencies were noted in the design validation phase.

These deficiencies include issues pertaining mainly to the mechanical and electronic design of the flex sensor and its integration with the prosthetic device. The following design recommendations are presented as an intention to nullify the deficiencies with the flex sensor which would improve size discrimination capabilities and in turn, improve the learnability of the design:

- Optimise the mechanical design of the flex sensor embodiment to accommodate a more effective means of conveying information to the user about the position of the prosthetic fingers.
- Optimise the microcontroller (electronic design) commands to distinguish a range of positions more clearly and definitively. Investigate the incorporation of music beat-like vibrations to illustrate different positions of the fingers (a more intuitive means to convey feedback instead of generic pulse vibrations).
- Investigate the addition of more flex sensors to provide a more holistic sensing capability to the device.

- Investigate the addition of a participant/user calibration system to custom calibrate the vibration motors per user (since vibration intensity perception could vary amongst individuals).

Additionally, it is recommended to investigate the incorporation of tilt sensors to optimise the operation of the device by turning off the capacitive sensors positioned on the anterior surface of the prosthetic device. This will ensure no sensor is accidentally triggered when the user is walking with the device next to their body.

7.2 Future Work

After modifications, as per the recommendations in Section 7.1, are implemented to the design, the main aim for future work would be to test the device on the population for which it has been designed: transradial amputees. This thesis proves the first prototype of the sensory feedback system as a viable first iteration, but further testing is required; particularly in conjunction with a body powered prosthetic device that has been certified instead of one that is in its preliminary phases of design and development.

The following have been identified as key future work milestones and validation exercises:

- Revalidate the updated sensory feedback system through bench testing and using transradial amputee subjects. Additionally, collect occupational therapist (OT) feedback about the device as they will primarily be responsible for endorsing the device to amputees and providing the necessary training to amputees in the use of the device. Incorporate any changes to the device as per OT recommendations.
- Evaluate the scalability and manufacturability of the design by testing the system on multiple different body powered prosthetic devices.
- If the device is not compatible with many of the prosthetic devices currently on the market, evaluate the option of applying minor changes (or “tweaks”) to the current design to fit specific body powered prostheses on the market. This tests the adaptability of the embodiment design.
- Perform both a formative usability trial (consisting of at least five transradial amputees who use a body powered prosthesis paired with five occupational therapists) and a larger summative usability trial if the results of the formative usability trial are unsatisfactory to determine the usability of the device.

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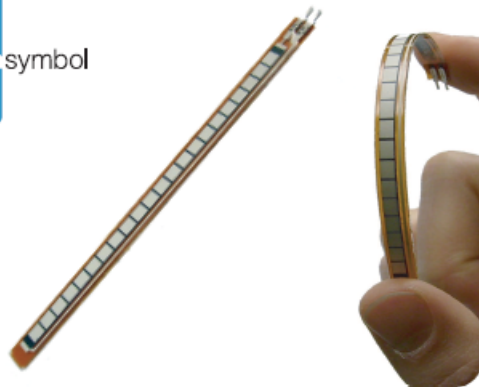
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Appendices

A.1 Flex Sensor Datasheet



FLEX SENSOR FS

Features

- Angle Displacement Measurement
- Bends and Flexes physically with motion device
- Possible Uses
 - Robotics
 - Gaming (Virtual Motion)
 - Medical Devices
 - Computer Peripherals
 - Musical Instruments
 - Physical Therapy
- Simple Construction
- Low Profile

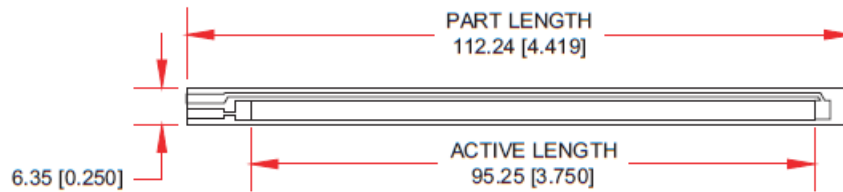
Mechanical Specifications

- Life Cycle: >1 million
- Height: $\leq 0.43\text{mm}$ (0.017")
- Temperature Range: -35°C to $+80^{\circ}\text{C}$

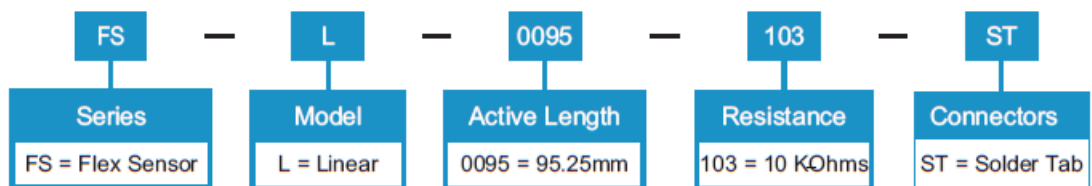
Electrical Specifications

- Flat Resistance: 10K Ohms $\pm 30\%$
- Bend Resistance: minimum 2 times greater than the flat resistance at 180° pinch bend (see "How it Works" below)
- Power Rating : 0.5 Watts continuous; 1 Watt Peak

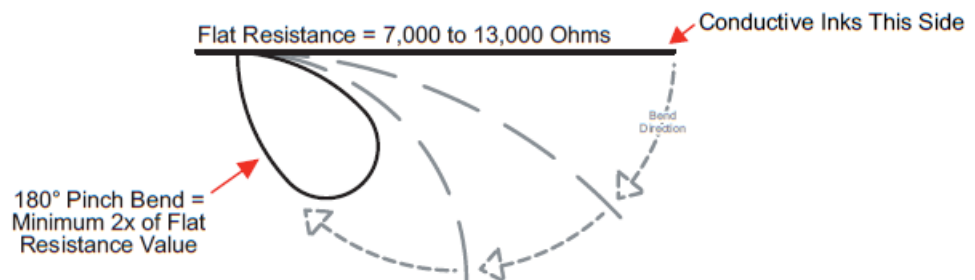
Dimensional Diagram - Stock Flex Sensor



How to Order - Stock Flex Sensor

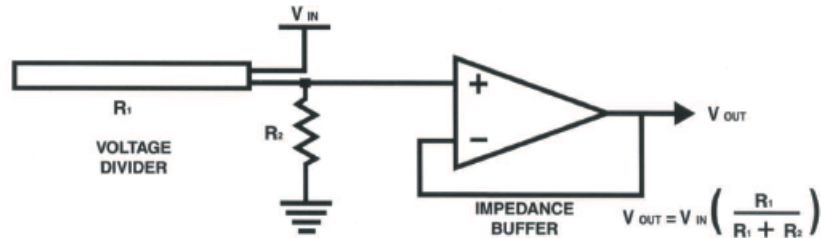


How It Works



Schematics

BASIC FLEX SENSOR CIRCUIT:

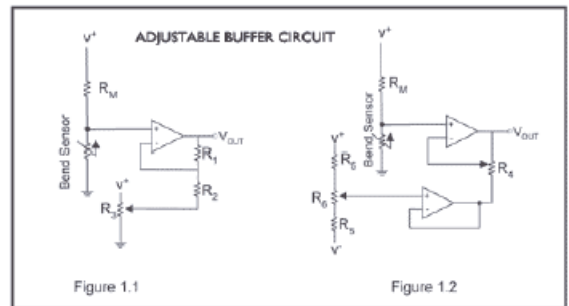


Following are notes from the ITP Flex Sensor Workshop

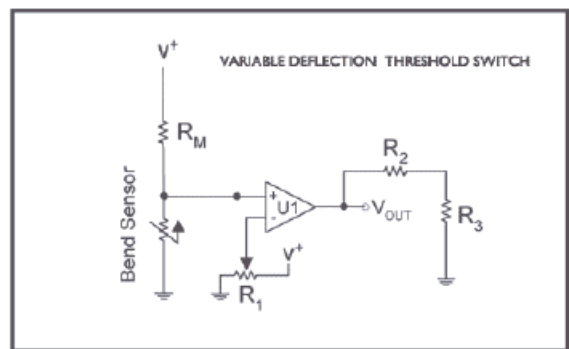
"The impedance buffer in the [Basic Flex Sensor Circuit] (above) is a single sided operational amplifier, used with these sensors because the low bias current of the op amp reduces error due to source impedance of the flex sensor as voltage divider. Suggested op amps are the LM358 or LM324."

"You can also test your flex sensor using the simplest circuit, and skip the op amp."

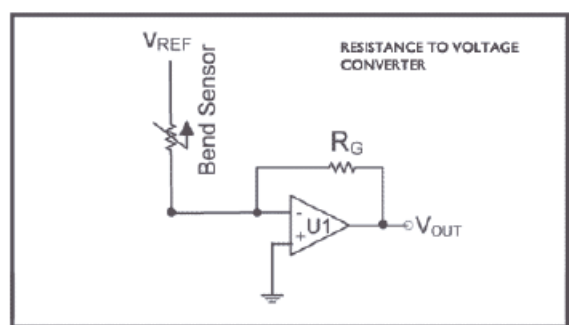
"Adjustable Buffer - a potentiometer can be added to the circuit to adjust the sensitivity range."



"Variable Deflection Threshold Switch - an op amp is used and outputs either high or low depending on the voltage of the inverting input. In this way you can use the flex sensor as a switch without going through a microcontroller."



"Resistance to Voltage Converter - use the sensor as the input of a resistance to voltage converter using a dual sided supply op-amp. A negative reference voltage will give a positive output. Should be used in situations when you want output at a low degree of bending."



A.2 Important Information for Arduino Pro Mini

A.3 Electronic Schematic of PCB for Sensory Feedback System

A.4 Arduino Code for Sensory Feedback System

```

#include <CapacitiveSensor.h> // Include
Capacitive Sensor library

const uint8_t t1_load = 0; //
Initialise compare value to zero
const uint8_t t1_comp = 244; //
8MHz/(1024*32) < 256 (2^8) *Must be less than 256

bool flag = 1; //
Initiate flag to TRUE (1)
int flexSensorPin = A0; // Flex
sensor pin linked to analog pin 0

CapacitiveSensor cs_2_4 = CapacitiveSensor(2,4); // Pin 2
(sensor pin) & Pin 4 (receive pin) - Dorsum
CapacitiveSensor cs_13_12 = CapacitiveSensor(13,12); // Pin 13
(sensor pin) & Pin 12 (receive pin) - Palm

int hap1 = 10; // Haptic
sensor 1 linked to Pin 10
int hap2 = 6; // Haptic
sensor 2 linked to Pin 6
int hap4 = 9; // Haptic
sensor 4 linked to Pin 9

volatile int counter1 = 0; // Counter
1 initialised to 0 (declared volatile as it will change)
volatile int counter2 = 0; // Counter
2 initialised to 0 (declared volatile as it will change)
int flex_value = 0; //
Initialise flex value to zero

void setup(){

  Serial.begin(9600); // Opens
serial port & sets data rate to 9600 bps

```

```

    cs_2_4.set_CS_Autocal_Millis(20000);           // Turn
off autocalibrate on channel 1
    cs_13_12.set_CS_Autocal_Millis(20000);       // Turn
off autocalibrate on channel 1

    TCCR2A = 0;                                   //Reset
Timer 2 Control Reg A

    TCCR2B = (TCCR2B & B11111100) | B00000111;   // Set
prescaler of 1024

    TCNT2 = t1_load;                             // Reset
Timer 2 and set compare value
    OCR2A = t1_comp;

    TIMSK2 = (1 << OCIE2A);                     // Enable
Timer 2 compare interrupt
}

void loop(){

long start = millis();                          // Returns
the number of milliseconds passed (uses Timer 0)

long total1 = cs_2_4.capacitiveSensor(30);      // Read
capacitive sensor 1 value
//Serial.print(total1);                        // Print
capacitive sensor 1 output
//Serial.print("\n");                          // Tab
character for debug window spacing

long total2 = cs_13_12.capacitiveSensor(30);    // Read
capacitive sensor 2 value
//Serial.print(total2);                        // Print
capacitive sensor 2 output
//Serial.print("\t");                          // Tab
character for debug window spacing

```

```

//Serial.println(counter1); // Print
counter 1 value

////////////////////////////////////
CAPACITIVE SENSOR 1: TOUCH AND PROXIMITY

if (total1 > 45 && flag) {

    if (total1 > 400 && counter1 < 64) { // HARD
Touch condition
        analogWrite(hap1, 255); // Turn
vibration ON FULL
    } else if (total1 > 400 && counter1 > 64) { // Holding
condition
        analogWrite(hap1, 0); // Turn
vibration OFF after 2 counts
    } else if (total1 > 200 && counter1 < 64) { // LIGHT
Touch condition
        analogWrite(hap1, 190);
        counter1 = 0;
    } else if (total1 > 200 && counter1 < 64) { // Turn OFF
vibration condition (object far away)
        analogWrite(hap1, 0);
    } else if (total1 < 200) { // No touch
        counter1 = 0; //
Initialise counter 4 to zero
    }

    if (total1 > 50 && total1 < 80) { // If
sensor value is between 40 and 200 (proximity sensor)
        analogWrite(hap1, 50); // Turn
vibration ON through PWM
        counter1 = 0; //
Initialise counter 4 to zero
    } else if (total1 > 80 && total1 < 150){
        analogWrite(hap1, 100);
    } else if (total1 > 150 && total1 <

```

```

200) {

    analogWrite(hap1, 140);
}

} else {
    analogWrite(hap1, 0); // Keep
vibration OFF if NO condition is met
}

////////////////////////////////////
CAPACITIVE SENSOR 2: TOUCH AND PROXIMITY

if (total2 > 45 && flag) {

    if (total2 > 400 && counter2 < 64) { // HARD
Touch condition
        analogWrite(hap2, 255); // Turn
vibration ON FULL
    } else if (total2 > 400 && counter2 > 64) { // Holding
condition
        analogWrite(hap2, 0); // Turn
vibration OFF after 2 counts
    } else if (total2 > 200 && counter2 < 64) { // LIGHT
Touch condition
        analogWrite(hap2, 190);
        counter2 = 0;
    } else if (total2 > 200 && counter2 < 64) {
        analogWrite(hap2, 0);
        //counter2 = 0;
    } else if (total2 < 200) { // No touch
        counter2 = 0; //

Initialise counter 4 to zero
    }

    if (total2 > 45 && total2 < 80) { // If sensor
value is between 40 and 200 (proximity sensor)

```

```

    analogWrite(hap2, 50); // Turn
vibration ON through PWM
    counter2 = 0; // Initialise
counter 4 to zero
    } else if (total2 > 80 && total2 < 150){
    analogWrite(hap2, 100);
    } else if (total2 > 150 && total2 <
200){

    analogWrite(hap2, 140);
    }

} else {
    analogWrite(hap2, 0); // Keep
vibration OFF if NO condition is met
}

////////////////////////////////////// FLEX
SENSOR: POSITION AND MOTION OF THE FINGERS

    flex_value = analogRead(flexSensorPin); // Read flex
sensor value

    if(flex_value < 300){ // If
fingers FULLY EXTENDED, vibration OFF

        TIMSK2 = (0 << OCIE2A);
        analogWrite(hap1, 0);
        analogWrite(hap2, 0);
        flag = 0;

        while(flex_value < 300){ // As
fingers begin to FLEX, vibration DECREASES

            flex_value = analogRead(flexSensorPin); //
Continuously read flex sensor value and re-evaluate
            //Serial.println(flex_value); // Debug

```

```

print

    if (flex_value < 170){ // As
fingers begin to FLEX more, vibration DECREASES
        analogWrite(hap4, 255); // Vibration
HIGHEST as flex begins (larger objects)
    } else if (flex_value < 220){
        analogWrite(hap4, 130);
    } else if (flex_value < 280){
        analogWrite(hap4, 80);
    } else if (flex_value < 300){
        analogWrite(hap4, 80); //
Vibration LOWEST as flex ends (smaller objects)
    }

}

TIMSK2 = (1 << OCIE2A); // Enable
Timer 2 and set compare value
    analogWrite(hap4, 0); // Turn
haptic OFF
    flag = 1;
} else if(flex_value > 320){ // Keep
haptics OFF if flex sensor is fully extended
    TIMSK2 = (1 << OCIE2A);
    analogWrite(hap4, 0);

}

}

ISR(TIMER2_COMPA_vect) { //
Interrupt function
    counter1++; //
Increment counter 1 by 32 each time
    counter2++; //
Increment counter 2 by 32 each time

```

```
TCNT2 = t1_load;
```

```
}
```

A.5 Raw Data from Sensor-Motor Combination Testing

Testee 1

| | Actual Triggered Sensor/s Location | Testee Perceived Location | Actual State of Haptic Motor | Testee Perceived State of Haptic Motor | Testee Felt Object Moving Closer To (And Away From) Sensor | Comments |
|-------------|------------------------------------|---------------------------|----------------------------------|--|--|--|
| HUMAN TOUCH | DH | DH | Hard Touch (HT) | HT | Y | |
| | PH | PH | Light Touch (LT) | LT | Y | |
| | AF | AF | Proximity (P) | P | Y | |
| | PF | PF | Hard Touch | HT | Y | |
| | PH & DH | PH, DH | Hard Touch, Proximity | HT, P | Y | |
| | PH & AF | PH, AF | Proximity, Hard Touch | P, HT | Y | |
| | PH & PF | PH, PF | Hard Touch, Light Touch | HT, LT | Y | |
| | PH & AF & PF | PH, AF, PF | Proximity, Proximity, Hard Touch | P, P, HT | Y | |
| | PH & AF & PF & DH | PH, AF, PF, DH | Proximity | P | Y | |
| METAL | DH | DH | Hard Touch | HT | Y | |
| | PH | PH | Light Touch | LT | Y | |
| | AF | AF | Proximity | P | Y | |
| | PF | PF | Hard Touch | HT | Y | |
| | PH & DH | PH, DH | Hard Touch, Proximity | HT, P | Y | |
| | PH & AF | PH, AF | Proximity, Hard Touch | P, HT | Y | |
| | PH & PF | PH, PF | Hard Touch, Light Touch | HT, LT | Y | |
| | DH | DH | Hard Touch | HT | Y | |
| WOOD | PH | PH | Light Touch | HT | Y | Can distinguish between proximity and touch but difficult to tell between light and hard |
| | AF | AF | Proximity | P | Y | |
| | PF | PF | Hard Touch | HT | Y | |
| | PH & DH | PH, DH | Hard Touch, Proximity | HT, P | Y | |
| | PH & AF | PH, AF | Proximity, Hard Touch | P, HT | Y | |
| | PH & PF | PH, PF | Hard Touch, Light Touch | HT, HT | Y | Can distinguish between proximity and touch but difficult to tell between light and hard |
| CERAMIC | DH | DH | Hard Touch | LT | Y | Temperamental, depends on the sensor and surface area of both the sensor and the material and the mug used |
| | PH | PH | Light Touch | LT | Y | |
| | AF | AF | Proximity | P | Y | |
| | PF | PF | Hard Touch | LT | Y | As above |
| | PH & DH | PH, DH | Hard Touch, Proximity | HT, P | Y | |
| | PH & AF | PH, AF | Proximity, Hard Touch | P, HT | Y | |
| | PH & PF | PH, PF | Hard Touch, Light Touch | HT, LT | Y | |
| GLASS | DH | DH | Hard Touch | P to LT | N | Little to know change in feedback. Any slight feedback felt may be due to the conductivity of tester's hand getting in the way |
| | PH | PH | Light Touch | LT | N | As above |
| | AF | AF | Proximity | P | N | As above |
| | PF | PF | Hard Touch | P | N | As above |
| | PH & DH | PH, DH | Hard Touch, Proximity | P, P | N | As above |
| | PH & AF | PH, AF | Proximity, Hard Touch | P, LT | Y | As above |
| | PH & PF | PH, PF | Hard Touch, Light Touch | P, P | N | As above |

Testee 2

| | Actual Triggered Sensor/s Location | Testee Perceived Location | Actual State of Haptic Motor | Testee Perceived State of Haptic Motor | Testee Felt Object Moving Closer To (And Away From) Sensor | Comments |
|-------------------|------------------------------------|---------------------------|----------------------------------|--|--|--|
| HUMAN TOUCH | DH | DH | Hard Touch (HT) | HT | Y | |
| | PH | PH | Light Touch (LT) | LT | Y | |
| | AF | AF | Proximity (P) | P | Y | |
| | PF | PF | Hard Touch | HT | Y | |
| | PH & DH | PH, DH | Hard Touch, Proximity | HT, P | Y | |
| | PH & AF | PH, AF | Proximity, Hard Touch | P, HT | Y | |
| | PH & PF | PH, PF | Hard Touch, Light Touch | HT, LT | Y | |
| | PH & AF & PF | PH, AF, PF | Proximity, Proximity, Hard Touch | P, P, HT | Y | |
| PH & AF & PF & DH | PH, AF, PF, DH | Proximity | P | Y | | |
| METAL | DH | DH | Hard Touch | HT | Y | |
| | PH | PH | Light Touch | LT | Y | |
| | AF | AF | Proximity | P | Y | |
| | PF | PF | Hard Touch | HT | Y | |
| | PH & DH | PH, DH | Hard Touch, Proximity | HT, P | Y | |
| | PH & AF | PH, AF | Proximity, Hard Touch | P, HT | Y | |
| | PH & PF | PH, PF | Hard Touch, Light Touch | HT, LT | Y | |
| WOOD | DH | DH | Hard Touch | HT | Y | |
| | PH | PH | Light Touch | LT | Y | |
| | AF | AF | Proximity | P | Y | |
| | PF | PF | Hard Touch | HT | Y | |
| | PH & DH | PH, DH | Hard Touch, Proximity | LT, P | Y | Can distinguish between proximity and touch but difficult to tell between light and hard |
| | PH & AF | PH, AF | Proximity, Hard Touch | P, HT | Y | |
| PH & PF | PH, PF | Hard Touch, Light Touch | LT, LT | Y | As above | |
| CERAMIC | DH | DH | Hard Touch | HT | Y | |
| | PH | PH | Light Touch | LT | Y | |
| | AF | AF | Proximity | P | Y | |
| | PF | PF | Hard Touch | LT | Y | Temperamental, depends on the sensor and surface area of both the sensor and the material and the mug used |
| | PH & DH | PH, DH | Hard Touch, Proximity | LT, P | Y | As above |
| | PH & AF | PH, AF | Proximity, Hard Touch | P, HT | Y | |
| PH & PF | PH, PF | Hard Touch, Light Touch | HT, LT | Y | | |
| GLASS | DH | DH | Hard Touch | P | N | Little to know change in feedback. Any slight feedback felt may be due to the conductivity of tester's hand getting in the way |
| | PH | PH | Light Touch | P | N | As above |
| | AF | AF | Proximity | P | N | As above |
| | PF | PF | Hard Touch | LT | Y | As above |
| | PH & DH | PH, DH | Hard Touch, Proximity | P, P | N | As above |
| | PH & AF | PH, AF | Proximity, Hard Touch | P, P to LT | Y | As above |
| PH & PF | PH, PF | Hard Touch, Light Touch | P, P | N | As above | |

Testee 3

| | Actual Triggered Sensor/s Location | Testee Perceived Location | Actual State of Haptic Motor | Testee Perceived State of Haptic Motor | Testee Felt Object Moving Closer To (And Away From) Sensor | Comments |
|-------------|------------------------------------|---------------------------|----------------------------------|--|--|--|
| HUMAN TOUCH | DH | DH | Hard Touch (HT) | HT | Y | |
| | PH | PH | Light Touch (LT) | LT | Y | |
| | AF | AF | Proximity (P) | P | Y | |
| | PF | PF | Hard Touch | HT | Y | |
| | PH & DH | PH, DH | Hard Touch, Proximity | HT, P | Y | |
| | PH & AF | PH, AF | Proximity, Hard Touch | P, HT | Y | |
| | PH & PF | PH, PF | Hard Touch, Light Touch | HT, LT | Y | |
| | PH & AF & PF | PH, AF, PF | Proximity, Proximity, Hard Touch | P, P, HT | Y | |
| METAL | PH & AF & PF & DH | PH, AF, PF, DH | Proximity | P | Y | |
| | DH | DH | Hard Touch | HT | Y | |
| | PH | PH | Light Touch | LT | Y | |
| | AF | AF | Proximity | P | Y | |
| | PF | PF | Hard Touch | HT | Y | |
| | PH & DH | PH, DH | Hard Touch, Proximity | HT, P | Y | |
| | PH & AF | PH, AF | Proximity, Hard Touch | P, HT | Y | |
| | PH & PF | PH, PF | Hard Touch, Light Touch | HT, LT | Y | |
| WOOD | DH | DH | Hard Touch | HT | Y | |
| | PH | PH | Light Touch | Medium to High Touch | Y | Can distinguish between proximity and touch but difficult to tell between light and hard |
| | AF | AF | Proximity | P | Y | |
| | PF | PF | Hard Touch | LT | Y | As above |
| | PH & DH | PH, DH | Hard Touch, Proximity | LT, P | Y | As above |
| | PH & AF | PH, AF | Proximity, Hard Touch | P, LT | Y | As above |
| CERAMIC | PH & PF | PH, PF | Hard Touch, Light Touch | LT, LT | Y | As above |
| | DH | DH | Hard Touch | LT | Y | As above |
| | PH | PH | Light Touch | P | Y | |
| | AF | AF | Proximity | P | Y | |
| | PF | PF | Hard Touch | P | Y | Temperamental, depends on the sensor and surface area of both the sensor and the material and the mug used |
| | PH & DH | PH, DH | Hard Touch, Proximity | LT, P | Y | Can distinguish between proximity and touch but difficult to tell between light and hard |
| | PH & AF | PH, AF | Proximity, Hard Touch | P, LT | Y | As above |
| GLASS | PH & PF | PH, PF | Hard Touch, Light Touch | LT, LT | Y | As above |
| | DH | DH | Hard Touch | P | N | Little to know change in feedback. Any slight feedback felt may be due to the conductivity of tester's hand getting in the way |
| | PH | PH | Light Touch | P | N | As above |
| | AF | AF | Proximity | P | N | As above |
| | PF | PF | Hard Touch | P | N | As above |
| | PH & DH | PH, DH | Hard Touch, Proximity | LT, P | N | As above |
| PH & AF | PH, AF | Proximity, Hard Touch | P, P | N | As above | |

| | | | | | | |
|--|---------|--------|-------------------------|------|---|----------|
| | PH & PF | PH, PF | Hard Touch, Light Touch | P, P | N | As above |
|--|---------|--------|-------------------------|------|---|----------|

Testee 4

| | Actual Triggered Sensor/s Location | Testee Perceived Location | Actual State of Haptic Motor | Testee Perceived State of Haptic Motor | Testee Felt Object Moving Closer To (And Away From) Sensor | Comments |
|-------------|------------------------------------|---------------------------|----------------------------------|--|--|--|
| HUMAN TOUCH | DH | DH | Hard Touch (HT) | HT | Y | |
| | PH | PH | Light Touch (LT) | LT | Y | |
| | AF | AF | Proximity (P) | P | Y | |
| | PF | PF | Hard Touch | HT | Y | |
| | PH & DH | PH, DH | Hard Touch, Proximity | HT, P | Y | |
| | PH & AF | PH, AF | Proximity, Hard Touch | P, HT | Y | |
| | PH & PF | PH, PF | Hard Touch, Light Touch | HT, LT | Y | |
| | PH & AF & PF | PH, AF, PF | Proximity, Proximity, Hard Touch | P, P, HT | Y | |
| METAL | PH & AF & PF & DH | PH, AF, PF, DH | Proximity | P | Y | |
| | DH | DH | Hard Touch | HT | Y | |
| | PH | PH | Light Touch | LT | Y | |
| | AF | AF | Proximity | P | Y | |
| | PF | PF | Hard Touch | HT | Y | |
| | PH & DH | PH, DH | Hard Touch, Proximity | HT, P | Y | |
| | PH & AF | PH, AF | Proximity, Hard Touch | P, HT | Y | |
| | PH & PF | PH, PF | Hard Touch, Light Touch | HT, LT | Y | |
| WOOD | DH | DH | Hard Touch | HT | Y | |
| | PH | PH | Light Touch | LT | Y | |
| | AF | AF | Proximity | P | Y | |
| | PF | PF | Hard Touch | HT | Y | |
| | PH & DH | PH, DH | Hard Touch, Proximity | HT, P | Y | |
| | PH & AF | PH, AF | Proximity, Hard Touch | P, LT | Y | Can distinguish between proximity and touch but difficult to tell between light and hard |
| | PH & PF | PH, PF | Hard Touch, Light Touch | LT, LT | Y | As above |
| CERAMIC | DH | DH | Hard Touch | LT | Y | As above |
| | PH | PH | Light Touch | LT | Y | |
| | AF | AF | Proximity | P | Y | |
| | PF | PF | Hard Touch | P | Y | Temperamental, depends on the sensor and surface area of both the sensor and the material and mug used |
| | PH & DH | PH, DH | Hard Touch, Proximity | LT, P | Y | As above |
| | PH & AF | PH, AF | Proximity, Hard Touch | P, LT | Y | As above |
| | PH & PF | PH, PF | Hard Touch, Light Touch | HT, LT | Y | |
| GLASS | DH | DH | Hard Touch | P | N | Little to know change in feedback. Any slight feedback felt may be due to the conductivity of tester's hand getting in the way |
| | PH | PH | Light Touch | P | N | As above |
| | AF | AF | Proximity | P | N | As above |
| | PF | PF | Hard Touch | P | N | As above |
| | PH & DH | PH, DH | Hard Touch, Proximity | LT, P | N | As above |
| | PH & AF | PH, AF | Proximity, Hard Touch | P, P | N | As above |
| | PH & PF | PH, PF | Hard Touch, Light Touch | P, P | N | As above |

A.6 HREC Formal Approval for Ethics



UNIVERSITY OF CAPE TOWN
Faculty of Health Sciences
Human Research Ethics Committee



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Groote Schuur Hospital
Observatory 7925
Telephone [021] 406 6492
Email: hrec-enquiries@uct.ac.za
Website: www.health.uct.ac.za/fhs/research/humanethics/forms

18 December 2020

HREC REF: 782/2020

A/Prof S Sivarasu

Division of Biomedical Engineering
Room 7.17 Anatomy Building-FHS
Email: sudesh.sivarasu@uct.ac.za
Student: gdrct003@myuct.ac.za

Dear A/Prof Sivarasu

PROJECT TITLE: A SENSORY FEEDBACK SYSTEM FOR IMPROVING TACTILE AND PROPRIOCEPTIVE PERCEPTION IN PARTICIPANTS USING A BODY POWERED PROSTHESIS WITH A HAND ATTACHMENT (MSC CANDIDATE- MS C GORDAN-GRANT)

Thank you for your response addressing the issues by the Faculty of Health Sciences Human Research Ethics Committee (HREC).

It is a pleasure to inform you that the HREC has **formally approved** the above-mentioned study, subject to adding a section for participant signature and Investigator signature to the Informed consent document; and the HREC and PI's contact details.

This approval is subject to strict adherence to the HREC recommendations regarding research involving human participants during COVID -19, dated 17 March 2020 & 06 July 2020.

Approval is granted for one year until the 30 December 2021.

Please submit a progress form, using the standardised Annual Report Form if the study continues beyond the approval period. Please submit a Standard Closure form if the study is completed within the approval period.

(Forms can be found on our website: www.health.uct.ac.za/fhs/research/humanethics/forms)

The HREC acknowledge that the student: Ms Catherine Gordon-Grant will also be involved in this study.

Please quote the HREC REF in all your correspondence.

Please note that the ongoing ethical conduct of the study remains the responsibility of the principal investigator.

Please note that for all studies approved by the HREC, the principal investigator **must** obtain appropriate Institutional approval, where necessary, before the research may occur.

Appendix Removed
Due to having unremovable
Signatures

A.7 Failure Modes and Effects Analysis

A.7.1 Risk Analysis

| Risk Analysis: Sensory Feedback System | | | | | Risk Evaluation | | |
|--|--|---|---|---|-----------------|----------|---------------|
| ID | Hazard | Failure Cases (Effect of Hazard) | Hazardous Situation | Harm | Probability | Severity | Acceptability |
| PS1 | Power Supply: Flammable Electrolytes | *Risk of fire or explosion due to flammable electrolytes within the battery caused by shorting the terminals of the battery, or caused by pressurised internals due to dropping, denting or crushing. | *Short the battery terminals by fast charging or Voltage Out wire connects to Ground wire. *Battery becomes damaged over time due to frequent dropping, denting or crushing leading to pressurised internals. | *Fire or explosion causing severe burns and discomfort to user. *Fire or explosion of the battery causing irritating smoke leading to further damage if inhaled. *Fire or explosion causing irreversible damage to the device embodiment and sensors. | 3 | 5 | N ACC |
| ES1 | Electronic Failure: Blown Haptic | *Haptic motor receives a voltage outside of its maximum (above 3.3V). | *Haptic burns out and stops working. | *Device requires maintenance as it cannot present the sensed information to the user. *Device functions unreliably without one of its haptics to feedback information to the user. | 4 | 3 | N ACC |
| ES2 | Electronic Failure: Blown Arduino Pin | *Sensor or haptic draws excessive current from Arduino pin causing it to burn out. | *Arduino pin ceases to function resulting in the sensor or haptic connected to the pin also to stop functioning. | *Device requires maintenance as it cannot present the sensed information to the user. *Device functions unreliably without one of its components to sense information or relay feedback to the user. | 4 | 3 | N ACC |

| | | | | | | | |
|-----|---|--|--|---|---|---|------|
| WD1 | Water Damage to Electronics | *Risk of damage to electronics (resulting in total failure of device or malfunctioning) when exposed to water (rain or total submersion). | *Excessive rain falling onto and inside of device (specifically sensors and electronics). *User submerges device in large quantity of liquid/water. | *Damage to the electronic system of the device leading to device failure or malfunctioning. *Electronics may stop working altogether or result in unreliable functioning of the device. | 2 | 4 | ACC* |
| FS1 | Flex Sensor Embodiment Malfunction: Inhibits Movement | *Risk of embodiment causing flexed finger to get stuck in place. *Risk of embodiment not being kept in place leading to flex sensor being knocked out of calibrated position. | *Embodiment hooks and gets stuck at the wrong angle of the finger. *Embodiment and/or flex sensor shifts out of place due to being knocked or purposefully moved leading to ineffective protection of the flex sensor and/or flex sensor being moved out of its calibrated position leading to unreliable readings and damage to flex sensor. | *Design of embodiment results in malfunction of the prosthetic operating as intended (cannot flex and extend as designed). | 3 | 2 | ACC* |

| | | | | | | | |
|-----|---|--|--|---|---|---|------|
| FS2 | Flex Sensor Embodiment Malfunction: Damage to Flex Sensor | *Risk of embodiment not preventing flex sensor bending beyond its maximum (resulting in damage). | *Embodiment and/or flex sensor shifts out of place due to being knocked or purposefully moved leading to ineffective protection of the flex sensor and/or flex sensor being moved out of its calibrated position leading to unreliable readings and damage to flex sensor. | *Design of embodiment does not protect the flex sensor from over-flexion resulting in damage to the sensor leading to inaccurate readings and unreliable functioning of the device. | 2 | 4 | ACC* |
| HE1 | Haptic Enclosure Causing Discomfort | *Risk of sharp edges of haptic enclosures causing discomfort to the user. | Sharp edges dig in to user's arm causing discomfort and leads to user not using the device. | *Damage to the user's skin. | 3 | 2 | ACC* |
| S1 | Sensor Disconnect | *Risk of sensors disconnecting from the system. *Risk of disconnected wire shocking the user. | *Sensor (capactive or flex) wire becomes damaged and disconnects from the system. *Sensor disconnect caused by damage to wire (either partial or complete). | *Disconnect of sensor from system will result in malfunctioning of the device (it cannot operate reliably or effectively without connection of sensors). *Risk of unintended electronic simulation to the user. | 1 | 3 | ACC |
| E1 | Damage to Embodiment | *Risk of embodiment tearing due to general wear and tear, or excessive force. | *User forcefully takes the embodiment off the prosthesis causing it to tear or become damaged. | *Embodiment cannot be put back on or be worn as intended leading to sensors not being in calibrated, secure positions leading to malfunctioning of the device. | 1 | 3 | ACC |

A.7.2 Risk Control Measures

| Risk Control | | | | Residual Risk | | |
|--------------|---|---|--|---------------|----------|---------------|
| ID | Risk Control Options | Risk Control Measure | Risk Control Verification | Probability | Severity | Acceptability |
| PS1 | *Design to encase electronics and battery safely to protect from damage such as dropping, denting or crushing. *Design to prevent terminals of the battery connecting to one another. | *Electronic housing 3D printed in ABS (strong, durable material) to encase the battery and all electronics to protect against damage such as dropping, denting or crushing of the battery. *Battery terminals are soldered on to a PCB which prevents terminals from accidentally connecting (prevent shorting of the battery). *Battery recharges using a designated charging board designed specifically for the battery (to prevent fast charging leading to damage). *Ensure battery safety circuit is securely attached. | *Section 3.3.5 details the design of the electronic housing and PCB. | 1 | 3 | ACC |
| ES1 | *Design to prevent excessive voltage applied to the haptic motors. | *Transistors are used as switches between the Arduino pin and haptic motor to: 1) protect the Arduino pin from excessive current draw from the haptic motor. *PCB design ensures haptic is connected to a 3.3V source (and not the 3.7V battery) . | *Section 3.3.2.2 details the design choices to mitigate this risk. | 1 | 3 | ACC |

| | | | | | | |
|-----|---|--|--|---|---|-----|
| ES2 | <p>*Design to prevent excessive current draw from Arduino pins.</p> | <p>*Transistors are used as switches between the Arduino pin and haptic motor to: 1) protect the Arduino pin from excessive current draw from the haptic motor. *Transistors are used to directly connect haptics to Arduino pin (but to isolate the haptic current draw from the pin).</p> | <p>*Section 3.3.2.2 details the design choices to mitigate this risk.</p> | 1 | 3 | ACC |
| WD1 | <p>*Design to be tested for waterproofing. *Encase electronics and battery in a housing that can protect from reasonable quantities of water (light rain). *User must be instructed and educated about the risk of water to the functioning of the device (the device is not intended to be used in water).</p> | <p>*3D printed embodiment of the device protects the sensors from water damage (the material is impenetrable by liquids/water). *ABS (material used for electronic housing) is watertight and resistant to water. Further evaluation of the watertight nature of the electronic enclosure is required.</p> | <p>*Embodiment of the system has been tested for water proofing (Section 4.1). *Further evaluation of the watertight nature of the electronic enclosure is required.</p> | 1 | 3 | ACC |
| FS1 | <p>*Design for protection of the flex sensor. *Design for optimum functioning of the prosthesis (the embodiment of the system must not alter or hinder the intended operation of the prosthesis). *Design such that embodiment cannot be knocked out of place to protect calibration of the flex sensor.</p> | <p>*Section 3.3 Table 3.3 goes into detail about the efforts made to ensure: 1) the flex sensor was protected from damage, 2) the embodiment did not hinder intended operation of the prosthesis and 3) the embodiment and flex sensor were kept in calibrated position.</p> | <p>*Section 3.3 Table 3.3. details the verification of risk control.</p> | 1 | 2 | ACC |

| | | | | | | |
|-----|--|--|---|---|---|-----|
| FS2 | <p>*Design for protection of the flex sensor. *Design for optimum functioning of the prosthesis (the embodiment of the system must not alter or hinder the intended operation of the prosthesis).</p> <p>*Design such that embodiment cannot be knocked out of place to protect calibration of the flex sensor. *Design for rigid placement.</p> | <p>*Section 3.3 Table 3.3 goes into detail about the efforts made to ensure: 1) the flex sensor was protected from damage, 2) the embodiment did not hinder intended operation of the prosthesis and 3) the embodiment and flex sensor were kept in calibrated position.</p> | <p>*Section 3.3 Table 3.3 details the verification of risk control.</p> | 1 | 3 | ACC |
| HE1 | <p>*Design for smoother, more comfortable edges</p> | <p>*Sharp edges were smoothed out (filleted) to provide more comfort to the user.</p> | <p>*Section 3.3.3.3 details the verification of the risk control.</p> | 1 | 1 | ACC |
| S1 | <p>*Design for safe wiring of the system to protect loose wires from being damaged.</p> | <p>*Section 3.3 Table 3.3 details the efforts made to ensure safe wiring was implemented with the vibrotactile armband. *PCB designed to have wires soldered on to the board to prevent disconnects.</p> | <p>*Section 3.3 Table 3.3 details the verification of risk control.</p> | 1 | 2 | ACC |
| E1 | <p>*Design for strong, durable material choice.</p> | <p>*TPU material is chosen for its durability. It is commonly added to other material to increase strength. See Section 3.3.3.2.</p> | <p>*Section 3.3.3.2 details the choice of material for the embodiment, stress test would need to be done to verify.</p> | 1 | 3 | ACC |

A.8 Raw Data from Participant Testing

| | Age | Upper Arm Diameter (cm) |
|----------------------|------------|--------------------------------|
| Participant 1 | 28 | 27 |
| Participant 2 | 25 | 29,5 |
| Participant 3 | 37 | 28 |
| Participant 4 | 27 | 31 |
| Participant 5 | 26 | 26,5 |

Figure 1: Participant Age and Upper Arm Diameter.

| Participant 1 | | | | | | | | | |
|---------------|-----------------------|--------------------------|-------------------|--------------------------|-------------------|-------------------------------------|-------------------|----------------|--------------------|
| Trial No. | Comparison (S1 vs S2) | Object Identification S1 | Response Time (s) | Object Identification S2 | Response Time (s) | Size Discrimination (S1 >, =, < S2) | Response Time (s) | Confidence (%) | Comments |
| 1 | S vs M | 0 | | 0 | | 0 | 16,96 | 60 | second one smaller |
| 2 | M vs S | 0 | | 0 | | 0 | 19,17 | 50 | same size |
| 3 | S vs S | 0 | | 0 | | 0 | 16,86 | 60 | second one larger |
| 4 | S vs S | 0 | | 0 | | 1 | 16,62 | 40 | same size |
| 5 | S vs L | 0 | | 0 | | 1 | 12,8 | 100 | second one larger |
| 6 | L vs S | 0 | | 0 | | 1 | 9,1 | 100 | second one smaller |
| 7 | M vs M | 0 | | 0 | | 0 | 12,96 | 50 | second one larger |
| 8 | M vs M | 0 | | 0 | | 0 | 14,62 | 50 | second one larger |
| 9 | M vs L | 0 | | 0 | | 1 | 11,47 | 100 | second one larger |
| 10 | L vs M | 0 | | 0 | | 1 | 12,96 | 90 | second one smaller |
| 11 | L vs L | 0 | | 0 | | 1 | 10,87 | 100 | same size |
| 12 | L vs L | 0 | | 0 | | 1 | 9,55 | 100 | same size |
| Total | | 0 | | 0 | | 7 | | 66,87306502 | |

| Participant 2 | | | | | | | | | |
|---------------|-----------------------|--------------------------|-------------------|--------------------------|-------------------|-------------------------------------|-------------------|----------------|--------------------|
| Trial No. | Comparison (S1 vs S2) | Object Identification S1 | Response Time (s) | Object Identification S2 | Response Time (s) | Size Discrimination (S1 >, =, < S2) | Response Time (s) | Confidence (%) | Comments |
| 1 | S vs M | 0 | | 0 | | 0 | 18,54 | 65 | equal size |
| 2 | M vs S | 0 | | 0 | | 0 | 18,5 | 60 | second one larger |
| 3 | S vs S | 0 | | 0 | | 0 | 16,77 | 70 | second one larger |
| 4 | S vs S | 0 | | 0 | | 1 | 18,47 | 70 | same size |
| 5 | S vs L | 0 | | 0 | | 1 | 27,15 | 20 | second one larger |
| 6 | L vs S | 0 | | 0 | | 1 | 17,35 | 90 | second one smaller |
| 7 | M vs M | 0 | | 0 | | 1 | 17,22 | 60 | equal |
| 8 | M vs M | 0 | | 0 | | 0 | 17,02 | 65 | second one smaller |
| 9 | M vs L | 0 | | 0 | | 0 | 13,77 | 80 | equal |
| 10 | L vs M | 0 | | 0 | | 1 | 12,7 | 70 | second one smaller |
| 11 | L vs L | 0 | | 0 | | 1 | 13,54 | 70 | equal |
| 12 | L vs L | 0 | | 0 | | 1 | 14,51 | 55 | equal |
| Total | | 0 | | 0 | | 7 | | 56,32788636 | |

| Participant 3 | | | | | | | | | |
|---------------|-----------------------|--------------------------|-------------------|--------------------------|-------------------|-------------------------------------|-------------------|----------------|----------------|
| Trial No. | Comparison (S1 vs S2) | Object Identification S1 | Response Time (s) | Object Identification S2 | Response Time (s) | Size Discrimination (S1 >, =, < S2) | Response Time (s) | Confidence (%) | Comments |
| 1 | S vs M | 0 | | 0 | | 1 | 16,06 | 30 | second larger |
| 2 | M vs S | 0 | | 0 | | 1 | 19,26 | 50 | second smaller |
| 3 | S vs S | 0 | | 0 | | 0 | 15,97 | 55 | second larger |
| 4 | S vs S | 0 | | 0 | | 0 | 15,3 | 50 | second larger |
| 5 | S vs L | 0 | | 0 | | 1 | 15,57 | 80 | second larger |
| 6 | L vs S | 0 | | 0 | | 1 | 15,31 | 60 | second smaller |
| 7 | M vs M | 0 | | 0 | | 1 | 14,54 | 50 | equal |
| 8 | M vs M | 0 | | 0 | | 1 | 15,45 | 50 | equal |
| 9 | M vs L | 0 | | 0 | | 0 | 11,73 | 70 | equal |

Figure 2: No Sensory Feedback (Part 1).

| | | | | | | | | | |
|-------|--------|---|--|---|--|---|-------|-------------|----------------|
| 10 | L vs M | 0 | | 0 | | 1 | 12,24 | 80 | second smaller |
| 11 | L vs L | 0 | | 0 | | 0 | 13,01 | 60 | second larger |
| 12 | L vs L | 0 | | 0 | | 1 | 13,02 | 50 | same size |
| Total | | 0 | | 0 | | 8 | | 53,53935297 | |

Participant 4

| Trial No. | Comparison (S1 vs S2) | Object Identification S1 | Response Time (s) | Object Identification S2 | Response Time (s) | Size Discrimination (S1 >, =, < S2) | Response Time (s) | Confidence (%) | Comments |
|-----------|-----------------------|--------------------------|-------------------|--------------------------|-------------------|-------------------------------------|-------------------|----------------|----------------|
| 1 | S vs M | 0 | | 0 | | 0 | 15,67 | 60 | second smaller |
| 2 | M vs S | 0 | | 0 | | 0 | 10,2 | 60 | same size |
| 3 | S vs S | 0 | | 0 | | 1 | 11,32 | 80 | saame size |
| 4 | S vs S | 0 | | 0 | | 0 | 9,55 | 80 | second smaller |
| 5 | S vs L | 0 | | 0 | | 1 | 9,18 | 100 | second larger |
| 6 | L vs S | 0 | | 0 | | 1 | 8,55 | 100 | second smaller |
| 7 | M vs M | 0 | | 0 | | 1 | 9,13 | 80 | same size |
| 8 | M vs M | 0 | | 0 | | 0 | 8,45 | 100 | second larger |
| 9 | M vs L | 0 | | 0 | | 1 | 7,16 | 100 | second larger |
| 10 | L vs M | 0 | | 0 | | 0 | 8,56 | 100 | equal |
| 11 | L vs L | 0 | | 0 | | 1 | 7,89 | 100 | same size |
| 12 | L vs L | 0 | | 0 | | 1 | 7,7 | 80 | same size |
| Total | | 0 | | 0 | | 7 | | 83,72093023 | |

Participant 5

| Trial No. | Comparison (S1 vs S2) | Object Identification S1 | Response Time (s) | Object Identification S2 | Response Time (s) | Size Discrimination (S1 >, =, < S2) | Response Time (s) | Confidence (%) | Comments |
|-----------|-----------------------|--------------------------|-------------------|--------------------------|-------------------|-------------------------------------|-------------------|----------------|----------------|
| 1 | S vs M | 0 | | 0 | | 1 | 11,32 | 70 | equal |
| 2 | M vs S | 0 | | 0 | | 0 | 10,54 | 30 | second larger |
| 3 | S vs S | 0 | | 0 | | 0 | 11,11 | 30 | second smaller |
| 4 | S vs S | 0 | | 0 | | 0 | 10,89 | 60 | second larger |
| 5 | S vs L | 0 | | 0 | | 1 | 11,21 | 90 | second larger |
| 6 | L vs S | 0 | | 0 | | 1 | 10,74 | 100 | second smaller |
| 7 | M vs M | 0 | | 0 | | 0 | 10,87 | 70 | second larger |
| 8 | M vs M | 0 | | 0 | | 0 | 9,54 | 70 | second smaller |
| 9 | M vs L | 0 | | 0 | | 1 | 10,12 | 80 | second larger |
| 10 | L vs M | 0 | | 0 | | 1 | 9,45 | 75 | second larger |
| 11 | L vs L | 0 | | 0 | | 0 | 9,12 | 50 | second smaller |
| 12 | L vs L | 0 | | 0 | | 1 | 9,89 | 85 | equal |
| Total | | 0 | | 0 | | 6 | | 58,56526048 | |

Figure 3: No Sensory Feedback (Part 2).

| Participant 1 | | | | | | | | | |
|---------------|-----------------------|--------------------------|-------------------|--------------------------|-------------------|-------------------------------------|-------------------|----------------|--------------------|
| Trial No. | Comparison (S1 vs S2) | Object Identification S1 | Response Time (s) | Object Identification S2 | Response Time (s) | Size Discrimination (S1 >, =, < S2) | Response Time (s) | Confidence (%) | Comments |
| 1 | S vs M | 1 | 4,3 | 1 | 6,19 | 0 | 5,7 | 70 | same size |
| 2 | M vs S | 1 | 2,78 | 1 | 6,2 | 1 | 6,61 | 80 | second one smaller |
| 3 | S vs S | 1 | 2,99 | 1 | 4,22 | 1 | 5,44 | 80 | same size |
| 4 | S vs S | 1 | 2,36 | 1 | 4,88 | 1 | 4,79 | 90 | same size |
| 5 | S vs L | 1 | 1,93 | 1 | 3,76 | 1 | 4,54 | 90 | second one bigger |
| 6 | L vs S | 1 | 1,84 | 1 | 7,34 | 1 | 4,45 | 100 | second one smaller |
| 7 | M vs M | 1 | 3,18 | 1 | 5,92 | 0 | 5,36 | 100 | second larger |
| 8 | M vs M | 1 | 2,49 | 1 | 6,41 | 1 | 5,3 | 90 | same size |
| 9 | M vs L | 1 | 2,27 | 1 | 5,78 | 1 | 4,89 | 100 | second one larger |
| 10 | L vs M | 1 | 1,83 | 1 | 3,2 | 1 | 4,44 | 100 | second one smaller |
| 11 | L vs L | 1 | 2,23 | 1 | 4,68 | 1 | 4,72 | 100 | same size |
| 12 | L vs L | 1 | 1,73 | 1 | 4,15 | 1 | 4 | 100 | same size |
| Total | | 12 | | 12 | | 10 | | 91,6666667 | |

| Participant 2 | | | | | | | | | |
|---------------|-----------------------|--------------------------|-------------------|--------------------------|-------------------|-------------------------------------|-------------------|----------------|--------------------|
| Trial No. | Comparison (S1 vs S2) | Object Identification S1 | Response Time (s) | Object Identification S2 | Response Time (s) | Size Discrimination (S1 >, =, < S2) | Response Time (s) | Confidence (%) | Comments |
| 1 | S vs M | 1 | 6,65 | 1 | 9,13 | 0 | 14,32 | 60 | equal size |
| 2 | M vs S | 1 | 5,55 | 1 | 7,59 | 1 | 12,44 | 90 | second one smaller |
| 3 | S vs S | 1 | 4,26 | 1 | 5,62 | 1 | 9,32 | 70 | equal size |
| 4 | S vs S | 1 | 5 | 1 | 7,9 | 1 | 10,08 | 80 | equal size |
| 5 | S vs L | 1 | 2,72 | 1 | 6,56 | 1 | 9,81 | 100 | second one larger |
| 6 | L vs S | 1 | 1,11 | 1 | 6,94 | 1 | 8,12 | 80 | second one smaller |
| 7 | M vs M | 1 | 1,79 | 1 | 7,46 | 1 | 6,47 | 70 | equal size |
| 8 | M vs M | 1 | 1,54 | 1 | 5,92 | 0 | 6,16 | 75 | second smaller |
| 9 | M vs L | 1 | 2,34 | 1 | 6,75 | 1 | 7,44 | 80 | second larger |
| 10 | L vs M | 1 | 1,54 | 1 | 5,19 | 1 | 6,68 | 100 | second smaller |
| 11 | L vs L | 1 | 1,67 | 1 | 4,15 | 1 | 5,43 | 80 | equal size |
| 12 | L vs L | 1 | 1,45 | 1 | 4,02 | 1 | 5,66 | 100 | equal size |
| Total | | 12 | | 12 | | 10 | | 82,0833333 | |

| Participant 3 | | | | | | | | | |
|---------------|-----------------------|--------------------------|-------------------|--------------------------|-------------------|-------------------------------------|-------------------|----------------|----------------|
| Trial No. | Comparison (S1 vs S2) | Object Identification S1 | Response Time (s) | Object Identification S2 | Response Time (s) | Size Discrimination (S1 >, =, < S2) | Response Time (s) | Confidence (%) | Comments |
| 1 | S vs M | 1 | 8,19 | 1 | 9,14 | 1 | 12,34 | 50 | second larger |
| 2 | M vs S | 1 | 6,06 | 1 | 7,12 | 1 | 13,02 | 60 | second smaller |
| 3 | S vs S | 1 | 6,24 | 1 | 6,74 | 1 | 12,91 | 70 | same size |
| 4 | S vs S | 1 | 6,32 | 1 | 5,77 | 1 | 11,34 | 60 | same size |
| 5 | S vs L | 1 | 5,19 | 1 | 6,62 | 1 | 11,87 | 90 | second larger |
| 6 | L vs S | 1 | 5,07 | 1 | 5,64 | 1 | 10,12 | 80 | second smaller |
| 7 | M vs M | 1 | 6,12 | 1 | 7,34 | 0 | 11,21 | 60 | second larger |
| 8 | M vs M | 1 | 4,56 | 1 | 6,23 | 1 | 10,76 | 80 | same size |
| 9 | M vs L | 1 | 5,79 | 1 | 5,48 | 1 | 9,67 | 70 | second larger |
| 10 | L vs M | 1 | 5,79 | 1 | 5,88 | 1 | 9,01 | 80 | second smaller |
| 11 | L vs L | 1 | 2,3 | 1 | 5,12 | 1 | 7,56 | 90 | same size |
| 12 | L vs L | 1 | 1,94 | 1 | 4,78 | 1 | 5,1 | 100 | same size |
| Total | | 12 | | 12 | | 11 | | 74,1666667 | |

Figure 4: Sensory Feedback (Part 1).

| Participant 4 | | | | | | | | | |
|---------------|-----------------------|--------------------------|-------------------|--------------------------|-------------------|-------------------------------------|-------------------|----------------|----------------|
| Trial No. | Comparison (S1 vs S2) | Object Identification S1 | Response Time (s) | Object Identification S2 | Response Time (s) | Size Discrimination (S1 >, =, < S2) | Response Time (s) | Confidence (%) | Comments |
| 1 | S vs M | 1 | 7,18 | 1 | 8,23 | 0 | 6,17 | 80 | second larger |
| 2 | M vs S | 1 | 8,35 | 1 | 7,85 | 1 | 5,9 | 80 | second smaller |
| 3 | S vs S | 1 | 7,6 | 1 | 6,55 | 1 | 4,17 | 80 | same size |
| 4 | S vs S | 1 | 6,68 | 1 | 6,14 | 1 | 3,89 | 80 | second larger |
| 5 | S vs L | 1 | 5,88 | 1 | 7,74 | 1 | 2,69 | 100 | second larger |
| 6 | L vs S | 1 | 5,69 | 1 | 7,34 | 1 | 2,13 | 100 | second smaller |
| 7 | M vs M | 1 | 6,12 | 1 | 6,88 | 0 | 1,78 | 100 | second smaller |
| 8 | M vs M | 1 | 5,76 | 1 | 5,45 | 1 | 2,43 | 80 | same size |
| 9 | M vs L | 1 | 6,18 | 1 | 6,12 | 1 | 2,3 | 100 | second larger |
| 10 | L vs M | 1 | 6,4 | 1 | 7,4 | 1 | 2,15 | 100 | second smaller |
| 11 | L vs L | 1 | 5,07 | 1 | 6,51 | 1 | 2,1 | 100 | same size |
| 12 | L vs L | 1 | 5,24 | 1 | 5,45 | 1 | 1,13 | 100 | same size |
| Total | | 12 | | 12 | | 10 | | 91,66666667 | |

| Participant 5 | | | | | | | | | |
|---------------|-----------------------|--------------------------|-------------------|--------------------------|-------------------|-------------------------------------|-------------------|----------------|----------------|
| Trial No. | Comparison (S1 vs S2) | Object Identification S1 | Response Time (s) | Object Identification S2 | Response Time (s) | Size Discrimination (S1 >, =, < S2) | Response Time (s) | Confidence (%) | Comments |
| 1 | S vs M | 1 | 8,5 | 1 | 8,65 | 1 | 3,31 | 60 | second larger |
| 2 | M vs S | 1 | 8,1 | 1 | 7,42 | 1 | 2,95 | 85 | second smaller |
| 3 | S vs S | 1 | 7,19 | 1 | 6,61 | 1 | 3,49 | 50 | equal |
| 4 | S vs S | 1 | 6,11 | 1 | 7,23 | 1 | 2,93 | 80 | equal |
| 5 | S vs L | 1 | 6,89 | 1 | 7,12 | 1 | 2,47 | 95 | second larger |
| 6 | L vs S | 1 | 6,48 | 1 | 6,55 | 1 | 1,65 | 95 | second smaller |
| 7 | M vs M | 1 | 7,3 | 1 | 5,14 | 0 | 2,13 | 70 | second smaller |
| 8 | M vs M | 1 | 6,27 | 1 | 5,89 | 0 | 2,55 | 60 | second smaller |
| 9 | M vs L | 1 | 6,9 | 1 | 5,56 | 1 | 1,66 | 100 | second larger |
| 10 | L vs M | 1 | 5,12 | 1 | 5,12 | 1 | 1,59 | 90 | second smaller |
| 11 | L vs L | 1 | 5,34 | 1 | 4,21 | 1 | 1,9 | 100 | equal |
| 12 | L vs L | 1 | 5,02 | 1 | 4,3 | 1 | 1,23 | 95 | equal |
| Total | | 12 | | 12 | | 10 | | 81,66666667 | |

Figure 5: Sensory Feedback (Part 2).