Tactile Feedback for Dexterous Manipulation Operations using Assistive Prosthetic Fingers

Daniel Kucherhan

A Thesis
Submitted in partial fulfillment of the requirements
for the degree of
Master of Applied Science in Biomedical Engineering

October 2017

Ottawa-Carleton Institute for Biomedical Engineering

School of Electrical Engineering and Computer Science
Faculty of Engineering
University of Ottawa

ABSTRACT

Dexterous manipulation operations using robotic or prosthetic fingers is seemingly facilitated with enhanced tactile feedback. Using a combination of artificial sensors and actuators, a tactile feedback system that conveys tactual information (force, pressure, & temperature) from an artificial fingertip to the user's hand is developed and tested with subjects. Results reveal that subjects are capable of distinguishing specific actuators with a high degree of accuracy. The sensor density and actuator fidelity of the feedback system is insufficient to yield performance equal to that of a human's natural tactile senses. Future studies are recommended to identify optimal tactile feedback sites as well as to discover a more robust system to be used in robotic and immersive virtual reality contexts.

ACKNOWLEDGEMENTS

I would like to express my sincere appreciation to my supportive spouse, Shari, and my two young daughters Sienna and Keira for their patience during the production of this work. My repeated absenteeism for research purposes and scholarly thoughts during family activities were met with acceptance and understanding. I look forward to spending more quality time with you upon completion of this contribution to the scientific community.

To Professor Emil Petriu, whose engaging discussions were filled with captivating cultural wit and insightful observations, I thank you. Your personal guidance has proven invaluable and your enthusiasm for the field of biological inspired haptics and robotics is quite apparent. I wish you a successful conclusion to such a profound academic career that has taken you to several countries around the world.

To my Bio-inspired lab mates: Thiago, my academic mentor and Ph.D candidate, and Vinicius (aka "Vinni F") the emerging ice hockey star I would like to say "Abrigado" for the many hours spent with silicone, robots and haptic devices in the BioIn lab of the SITE building at the University of Ottawa. To Miriam, co-researcher extraordinaire, who gave willingly of her time and knowledge during the experimental portion of this thesis, I would like to convey my deepest gratitude for your assistance and insightful suggestions throughout the process. So happy to have shared your company and to have made your acquaintance, all the best with the completion of your doctoral theses.

There is little doubt in my mind that I would not have returned to undertake a Master's thesis if I had not been sponsored to do so and provided with time away from my employer in order to pursue my academic endeavours. As such, I owe a great deal of gratitude to my employer, the Canadian Armed Forces, for allowing me to catch up on the scientific advances since I completed my undergraduate studies back in 2003

It has not been as easy as I expected to delve back into the books, but certainly the availability of modern online resources and advances in biotechnologies has facilitated this work. It has been an incredible adventure learning about the multi-disciplinary and multi-faceted world of biomedical engineering and my gratitude goes out to my peers and those researchers who have come before me for their ingenuity to create solutions that benefit of humanity. The future is bright for this emerging field.
DK

CONTENTS

LIST OF FIGURES

LIST OF TABLES

GLOSSARY OF TERMS

CNS – central nervous system

DEA – Dielectric Elastomer Actuator

EAP – Electrically Active Polymer

FA – Fast Acting

FSR – Force Sensing Resistor

IPN – Interpenetrating Polymer-Elastomer Network

LRA – Linear Resonant Actuator

MOSFET – Metal-Oxide-Semiconductor Field-Effect Transistor

PNS – peripheral nervous system

PVDF – Polyvinylidene Flouride

SA – Slow Acting

SAW – Surface Acoustic Wave

SMA – Shape Memory Alloy

CHAPTER 1 – INTRODUCTION

1.1 Context

Tactile systems are the very foundation of environmental interaction. Operating in a vivid and rich tactile enviro-sphere, the innate ability to both perceive and manipulate one's surroundings using the sense of touch has evolved over hundreds of thousands of years and has enabled sentiency of the human race. Although it is considered one of the most primitive senses that a human possesses, it is difficult to comprehend how one could survive without the sophisticated, interactive abilities and auto-defence mechanisms that humans make use of on a daily basis. The under-stated and often overlooked sense of touch tends to be superseded by its more common sensory counterparts in popular literature and its complexities tend to be taken for granted by humankind. Touch plays a crucial role for humans, as emphasized in the following quote from R. Sekuler and R. Balke: "… touch can be constructed as the most reliable of the sensor modalities. When senses conflict, touch is usually the ultimate arbiter" [1]. Although much research effort has been invested into vision-based systems in recent years, robotic and prosthetic tactile feedback research has comparably achieved more modest advancement.

Human haptic technology has advanced much slower than its vision sensing counterparts over the last decade, arguably due to the surging demand for digital video applications in several research areas, such as robotics, as well as the inherent limitations of modern technologies to viably reproduce the multi-faceted, tactile experiences in the real world. Limitations such as sensor integration and analysis or translation of high-volume, sensory data streams, have proven to be unwieldly in both size and complexity. Modern artificially produced tactile feedback systems tend to be singularly-purposed systems, constructed for simple applications, producing a unidimensional actuator output. There remains much unlocked potential for major advancements in haptic systems engineering before an artificial tactile feedback system can rival the full spectrum of multi-dimensional and dynamic haptic abilities of living organisms.

With thousands of mechanoreceptors, hundreds of grams of brain matter, and many meters of nerve fibres, no two humans share a completely identical tactile system blueprint. The tactile sense is unique to each individual. With several years of tactile training, humans are able to perform basic dexterous manipulation operations, such as grasping and carrying fine objects, writing with a pencil, and identify items simply by touching them. Humans are also capable of rapid perception-to-action cycles and can detect very subtle changes in environmental conditions. Indeed, given a human body's evolved tactile blueprint, designers of artificial tactile feedback systems have difficulty in creating a system that can compete with such an innate and sophisticated system.

Collins English Dictionary [2] provides a clear definition of the two key terms, "touch" and "tactile" used though this thesis: "The sense by which the texture and other qualities of objects can be experienced when they come in contact with a part of the body surface, especially the tips of the fingers." The term "haptic" is derived from the Greek word *haptikos* meaning 'able to grasp' and from *haptein* meaning 'fasten' [3]. The word 'haptic,' in its most classical sense, is used as an adjective, as in: "*…relating to the sense of touch, in particular relating to the perception and manipulation of objects using the senses of touch and proprioception."* However, in modern parlance, it has also been adopted for use in the more common form of a noun. Referring to digital technology, this noun is often used in a sentence (e.g. "…through the use of joysticks and other haptics."). Haptics differs from tactile sensing in so much that tactile events are more passive and processed "…solely by the sensory receptors located in the skin," where haptics "…involves a combination of cutaneous stimulation [tactile] along with kinesthetic and other motor feedback" [4]. Human haptic perception, is the result of an active

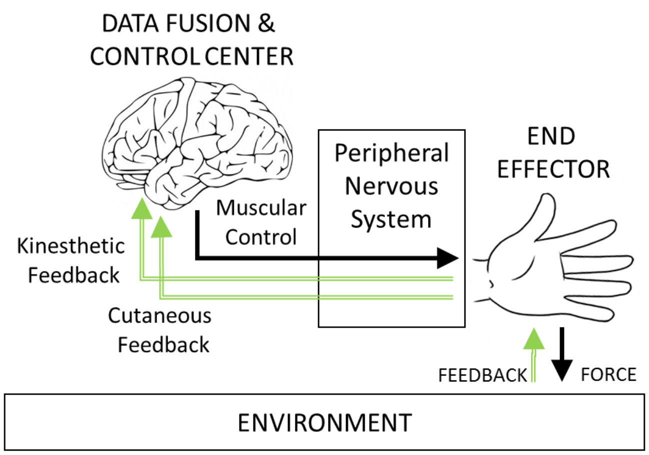


Figure 1-1. Cutaneous/Tactile and kinesthetic components of human haptic perception (green).

investigatory dexterous manipulation act involving two distinct components as illustrated in Fig. 1-1:(i) Cutaneous information from touch sensors which provide about the geometric shape, contact force, elasticity, texture, and temperature of the touched object area. The highest density of cutaneous sensors is found in fingertips (but also in the tongue, the lips, and the foot). Force information is mostly provided by sensors on muscles, tendons and bone joints proprioceptors; (ii) kinesthetic information about the positions and velocities of the kinematic structure (bones and muscles) of the hand [5].

For victims of an index finger amputation, the loss of a single part of the body with such a dense population of cutaneous and kinesthetic mechanoreceptors actually represents a dramatic reduction in tactile sensory fidelity. As was the case with a friend in college, who lost his index finger while opening a washing machine during the spin cycle, there was no artificial substitute for his natural senses and no way to simply grow back the loss of tactile feedback. He was the main motivation for this study into the realm of enhanced tactile feedback possibilities. Surely with today's abundant microelectronic technologies it would be possible to non-invasively remap some of the key tactile sensations from an artificial finger to another part of the body. This technology could potentially enhance dexterous manipulation performance and also be used by others to perceive sensations from remote robotic hands or in virtual reality environments. Additionally, a greater understanding of the tactile elements of the human body may provide insight into necessary components of an artificial, robotic tactile system, thereby enabling robots and humans to come into closer contact.

We are at the junction of a major revolution in the field of robotics and a new chapter in the medical world. Significant developments in microelectronic computing and communication technologies over the past half century, combined with society's growing dependence upon them, will result in a more intimate relationship between humans and robots. Aging populations in developed parts of the world will serve as a catalyst for making these currently clumsy and singular-purposed machines more esthetically pleasing, able to fulfill a wider variety of tasks, and most importantly capable of safely touching and interacting with their human creators. Though at this time, robots are mainly used for industrial purposes and are employed in environments hazardous to humans, such as nuclear disaster areas or for deep space exploration, the future will bring interactive-care machines to the home-front and to hospital wards. The beginnings are already here, as surgical robots are now routinely employed by operating-room surgeons to perform minute incisions and stitching of tissues that reduce a patient's recovery time. And yet ironically, one of the last remaining obstacles standing in the way of bringing robots and humans closer together is the barrier of touch; creating a robot that is sufficiently dexterous to perform dexterous manipulation tasks as well as realizing safe, physical interaction with humans.

1.2 Research Objectives and Contributions

The purpose of this study is to investigate how the highly sensitive tactile sensations commonly felt in the human fingertip can best be remapped to a different part of the dermis on the hand. This non-invasive remapping will benefit those who wear a prosthetic finger, for those who seek to remotely operate assistive robotic fingers for dexterous manipulation tasks.

OBJECTIVES

The objective of this thesis is to study and provide experimentally based answers to the following questions:

Q1: Can the tactile fingertip sensations of temperature, pressure, low & high vibrations and texture be adequately remapped to another part of the human hand?

Q2: Can a human equipped with a remapped tactile feedback module accurately identify changes in temperature, pressure, low & high vibrations as well as texture from sensors located on: a prosthetic finger, a remotely controlled robotic finger, and/or a bionic supplementary finger?

Q3: What efficacy does a tactile feedback module have in enhancing performance when using a prosthetic, an assistive bionic finger, or a remotely controlled robotic hand whilst conducting dexterous manipulation operations?

CONTRIBUTIONS

This thesis makes the following contributions:

C1. Reports the state of the art in tactile feedback techniques and technologies.

C2. Designs a prototype to test currently available tactile sensing and feedback solutions for use for the following applications:

a. Prosthetic finger;

b. Remote robotic finger; and

c. A bionic 'sixth' finger used for assistive grasping.

C3. Evaluates tactile sensor feedback techniques through experimentation with human subjects using assistive prosthetic finger(s).

C4. Provides recommendations for enhancements to tactile sensor and feedback solutions for (i) finger prosthetics, and (ii) remotely controlled robotic manipulation operations.

1.3 Publications Arising from Thesis

1. V. Prado da Fonseca, D.J. Kucherhan, T.E. Alves de Oliveira, D. Zhi, E.M. Petriu, “Fuzzy Controlled Object Manipulation using a Three-Fingered Robotic Hand,” *Proc. 11th Annual IEEE Int. Systems Conference - SysCon 2017*, pp. 346 - 351, Montreal, Que., Canada, April 2017.

2. D.J. Kucherhan and V. Prado da Fonseca, “Reactive Semi-Autonomous Home Care Robotics,” University of Ottawa Graduate Poster Competition, April 2016.

1.4 Outline

This thesis will examine human tactile performance when augmented with non-invasive, artificial sensors as well as feedback and control mechanisms. **Chapter 2** will review existing works that are related to this thesis and provide a solid foundational context. **Chapter 3** highlights the design and fabrication of the tactile prototype (sensor, feedback module and bionic assistive finger) constructed for the purposes of experimentation. **Chapter 4** details the experiments using both the artificial sensor and the feedback module to recognize tactile sensations. Result analysis and Conclusions will be described in the two remaining **Chapters 5 & 6**, respectively.

CHAPTER 2 – FOUNDATIONAL PRINCIPLES

What follows is a literature review of the building blocks of the human haptic system, based on touch, the terminology and characterization of tactile perception, the methods and means used for artificially capturing tactile information, a comparison of the main types of tactile feedback stimulation devices, and a summary of some of the major sensory remapping innovations in recent years.

2.1 Human Haptic System

The exact behaviour and characteristics of the haptic sensory system had eluded humanity for thousands of years. Though the mere existence of tactile sensors played a crucial role in humankind's evolution and survival, the earliest known recorded references to the human body's haptic abilities date back to ancient Indian, Chinese and Greek philosophers who articulated their understanding of the human's sense of touch in relation to cardinal points, elements and the other senses [6]. Although Aristotle (384-322 B.C.) expanded upon previous associations by contending that "…each function [sense organ] is assigned to a specific object [perception]." The Aristotelian view denoted that the heart was the organ of the sense of touch and that the object of perception was resident within the body instead of outside it: the flesh. This viewpoint held popular view until well after the Middle Ages, showing how advanced his theories were for his time [7].

Pivotal philosopher St. Thomas Aquinas (1224-1274) in his own version of *De anima*, approved Aristotle's belief that "…without touch there would be no other senses," but argued that the sense of touch was not merely like the other senses where a 'hybrid' form of mental and physical change is already present [8]. Rather, Aquinas' elevated the importance of the haptic sense to the top of the sensory list, contesting that touch is the only sense by which "…a material transcription takes place."

Progressive thinking on the sense of touch was once again reinvigorated through several others in the 19th Century, such as German pedagogue Johann Christoph Gutsmuth (1759-1839) "…who promoted…'exercises in feeling' for school children." Or Rousseau, who warned not to perform hard manual labour, concerned that tactile sensitivity would be lost with the resulting rough calloused skin [9]. But it was not until Ernst Heinrich Weber (1795-1878) that the tactual physiology was systematically and experimentally investigated [10]. What he termed as 'sensorial circles,' he described as acutely temperature and pressure sensitive areas of the skin that were assigned one or more nerves, and further he pioneered the observation that two compass points could not be discernable beyond a certain distance on the skin (later entitled the *'simultaneous space threshold'* by Max Von Frey (1852-1932)). Physiology would continue to play an increasing role in the distinction of the sense of touch into the 20th Century, with an increased understanding of the microscopic elements that permit tactile sensing.

The advent of microscopy and related technologies facilitated research regarding the nature of human haptics. However, research was stifled in part due to incongruent research disciplines. A great deal of knowledge regarding the functioning of the hand "…was originally derived from two separate but related scientific disciplines, namely, psychophysics and single-unit neurophysiology. It was Mountcastle (1967) who provided the critical impetus to combine these two…understand sensory performance and its underlying neural mechanisms" [11]. Though the main purpose of the two inter-related disciplines was similar, the methodologies and techniques employed were significantly different, in particular the types of subjects (humans or animals) used during experimentation. Further, where psychophysics attempted to derive mathematical functions that modelled the relation between physical events and tactual sensory experiences (physical-mental), neurophysiolocial studies primarily focused on physical events and the response of single nerve fibre events (physical-neural). Two Swedish investigators, Vallbo & Johansson, made efforts to bridge these two scientific domains and have attempted to develop a more standardized lexicon of haptic sensing principles.

2.1.1 The Tactile Sensory Receptors

The human body is endowed with several categories of sensory receptor cells and nerve endings that have evolved over hundreds of thousands of years and are specifically tuned to specific stimuli derived from the surrounding environment. The sensors found within the human body act as transduction receptors that convert energy, force and/or object composition into usable signals for the host. For example, sensor receptor cells within an eye's retina detects wavelength and intensity of light, just as receptor cells found within the skin are able to detect force, pressure, vibration, skin-stretch, and changes in temperature. Through the combination of the received information from the cells involved in tactual perception, humans are able to infer several additional characteristic sensations, such as slippage, wetness, as well as to several geometric and material object-related properties [11].

Mechanoreceptors are the most prevalent category of periphery sensory receptor cells and as their name implies, are mechanically activated through force, pressure, vibration and/or stretch. Thermal information is transduced subcutaneously via two types of thermoreceptors, which activate in response to thermal changes: warm and cold [12]. Lastly, there is a category of periphery nerve afferent responsive to intense changes in several forms of energy (e.g. chemical, mechanical, electrical, thermal) called Nociceptors [13]. Though cellular sensors are also present in muscles and joints, this paper will be primarily focused upon the subcutaneous mechano- and thermoreceptors located at the body's periphery, more specifically, found within the human hand.

There are two distinctive types of skin found on the human body: glabrous skin and hairy skin. In glabrous skin, such as found on the palm and inner-fingers of each hand, there are four principle types of subcutaneous tactile sensory cells, or mechanoreceptors, as identified in Figure 2-1 [14]. Each sensor cell type has a relative size, a relative depth from the skin's surface, density and consequently each cell also possesses a relative responsiveness to types of tactile stimulus. As the dermal layers act as a type of bandpass filtering, the deeper that the cell lays beneath the epidermis, the larger the receptive field and the more responsive to higher frequencies the mechanoreceptor cell becomes. Fast-acting (FA) and slow-acting (SA) cell responses will be further detailed in the next sub-section. Characteristics of each mechanoreceptor found in glabrous dermal tissue are summarized in Table 2-1 [11][14]. The mechanoreceptors found in hairy skin are similar with the exception of an additional FA mechanoreceptor at the base of each hair follicle, making these receptors the most sensitive to air currents and superficial touch.

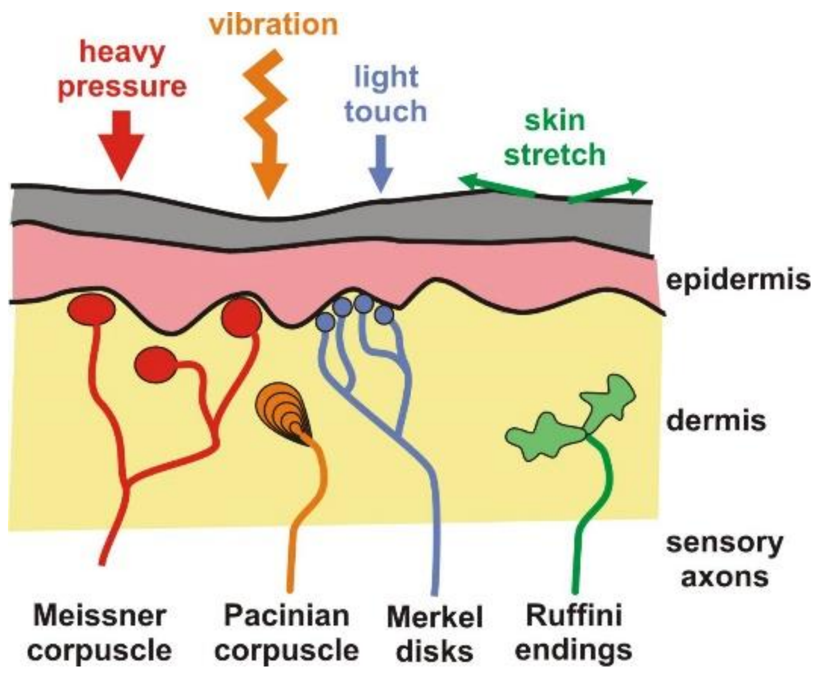


Figure 2-1. The four principle types of tactile, mechanoreceptor sensory cells located subcutaneously in glabrous skin: Meissner corpuscle, Pacinian corpuscle, Merkel disks, and Ruffini endings. Courtesy of [14].

GLABROUS SKIN MECHANO RECEPTORS	Purpose	diameter (length x width)	Min. detectable displacement	Detectable vibrotactile frequencies	Receptive Field	Fingertip Density (per mm²)	Skin Depth
FA I - Meissner	grip, texture changes	30-140 µm x 40-60 µm	1-40µm	3-40Hz	3-5mm	1.5	Epidermis (shallow)
FA II - Pacinian	Heavy pressure, high vibr	1000 µm x 500 µm	1-40µm	40-500Hz	Very large	350 each finger, 800 on palm	Subcutis (deep)
SA I - Merkel	Light force	< 20 µm²	50-120µm	0.5-3Hz	2-3mm	1	Epidermis (shallow)
SA II - Ruffini	Skin and joint stretch	Variable	50-120µm	0.1-0.5+kHz	10-15mm	0.1	Dermis (middle)

Table 2-1. Characteristics of the four principle mechanoreceptors in glabrous skin. FA = Fast Adapting (responsive to changes in stimulus, not static stimulus), SA = Slow Adapting (responsive to static stimulus). Adapted from [11][14].

Density of the receptors is quite variable and research has shown that the distribution of mechanoreceptors varies according to location on the body. On the hand for example, FA I Meissner corpuscles are most prevalent on the tips of the fingers, whereas SA II Ruffini endings are more densely positioned in the palm of the hand, as illustrated in Figure 2-2. [15] The specific distribution of mechanoreceptors, very much like human fingerprints, is unique to each human body. It is estimated that there are 17000 mechanoreceptors in a single human hand.

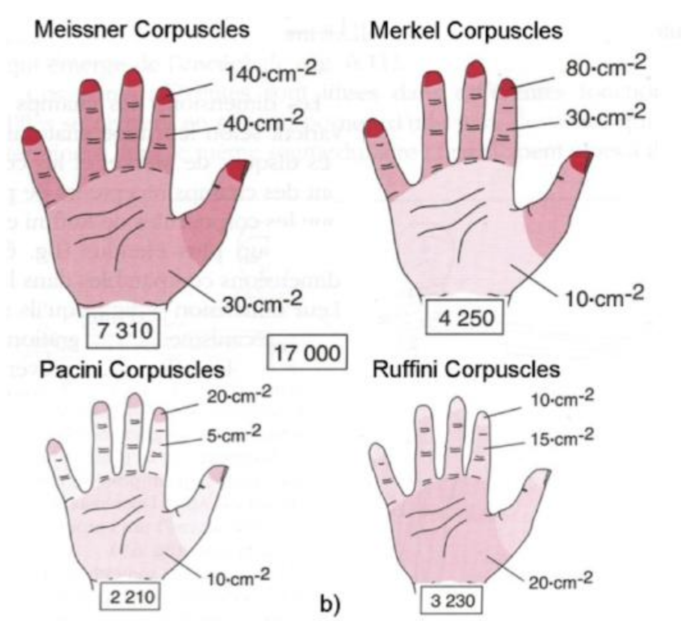


Figure 2-2. Relative mechanoreceptor densities in the human hand. Adapted from [15].

With respect to thermoreceptors, sensations such as hot and cold stem from two types of related free nerve endings located in the epidermis and dermis skin layers [12]. Although the exact densities of warm and cold thermoreceptors in glabrous and hairy skin has not been studied, it is known that the more numerous cold receptors respond to decreases in temperature ranging between five and forty degrees [16]. These cold thermoreceptors discharge most rapidly at 25°C to changes in temperature. Warm thermoreceptors, on the other hand, discharge with increasing temperature and are most active at 45°C [16].

2.1.2 The Nervous System

The neurophysiological basis behind the transduction of tactile-related stimuli has been studied with increasing intensity since 1967 [17][18]. As more miniaturized instruments became available to scientists, such as the tungsten microelectrode, capable of percutaneous recording of nerve impulses, the more insight into how the body relays tactual data from the mechanoreceptor to the brain. Neurophysiologist pioneers, Johansson & Vallbo, studied the hand in great detail, isolating both mechanoreceptors and afferent nerve fibres in human subjects. Their work laid the foundation for modern understanding of tactile physiology, tactual neuro-encoding and receptor behaviours.

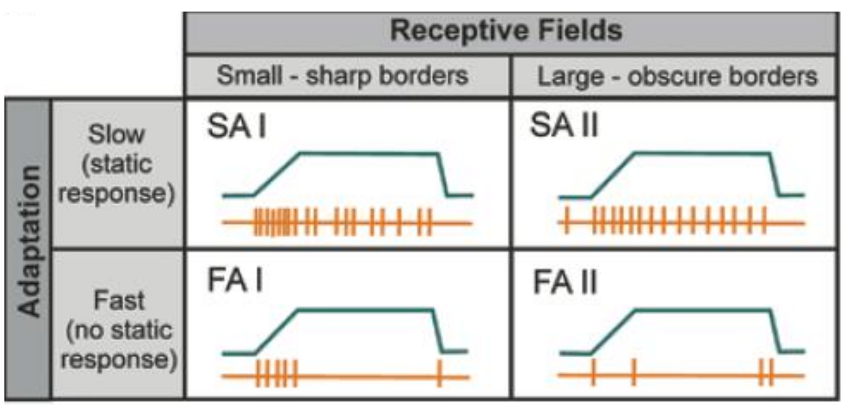


Figure 2-3. Spatial and temporal characteristics of mechanoreceptor responses to an indenting probe. Green lines represent temporal profiles of probe, while orange ticks show action potentials generated from the four types signal encoding of mechanoreceptors. Adapted from [18][19].

As eluded to in the previous subsection, there exists a tactual neuro-encoding that is transmitted along afferent nerve fibres to the brain. The four types of mechanoreceptors have two classifying traits describing their behaviour: receptive field and adaptation (see Figure 2-3) [18][19]. Receptive field refers to the spatial acuity of the mechanoreceptor to stimulus. Adaptation relates to how the mechanoreceptor discharges when stimulated. SA cells discharge when presented with dynamic as well as static stimuli, however FA receptors only discharge during a dynamic stimulus change (i.e. increasing or decreasing force).

The peripheral nervous system (PNS), a branched network of increasingly smaller axon nerve fibres as one reaches the extremities of the body, is responsible for the transmission of sensor receptor data (sensory division) via afferent nerves, as well as transmission of control data to the muscular system (motor division) via efferent nerves [20]. The PNS interfaces with the central nervous system, comprising of the spinal cord and the brain, at the dorsal root ganglion neuron on the dorsal root of a spinal nerve. "The cell body of these neurons have two branches, one that projects to the periphery and the other to the CNS" [12]. A dermatome is an area of skin that is innervated by a single dorsal root and a dermatomal map is used to diagnose spinal cord injury damage in humans.

Axons employ a complex cellular, biochemical activation trail to carry the data from dermatome to the primary sensory cortex. This remarkable, loss-less, transmission pathway is capable of conduction velocities of up to 120m/s in mammalian myelinated axons and is based upon the following formula: $v = 6d$ (where v is conduction velocity in metres/second and d is the diameter of the myelinated axon in µm) [21]. Due to the relatively thin nerve endings that relay mechanoreceptors and thermoreceptors data (ranging between 0.5 - 5µm), the nerve impulses for tactual and thermal data travel at velocities ranging between 3 – 30m/s [22]. Once a nerve cell has been triggered by a depolarizing threshold potential sufficient to cause cellular activation, there is a rapid influx of sodium ions and a more gradual conductance change in the efflux of potassium ions, which over time will reset to initial ionic concentration values. The depolarization of the cell causes adjacent nerve cells to depolarize, and the chain reaction continues, eventually generating a nerve impulse called an action potential. Given the relative and absolute refractory period of a nerve cell, the average reset period for a cell is in the order of 2ms, therefore making it possible to obtain a throughput in the order of 500 impulses / second [21]. It should be noted at this point that much has been assumed in much of the literature that each individual mechanoreceptor is a termination point for a single afferent nerve fibre. However, more recently, it has been questioned whether groups or clusters of receptor cells can cause the activation of multiple fibres.

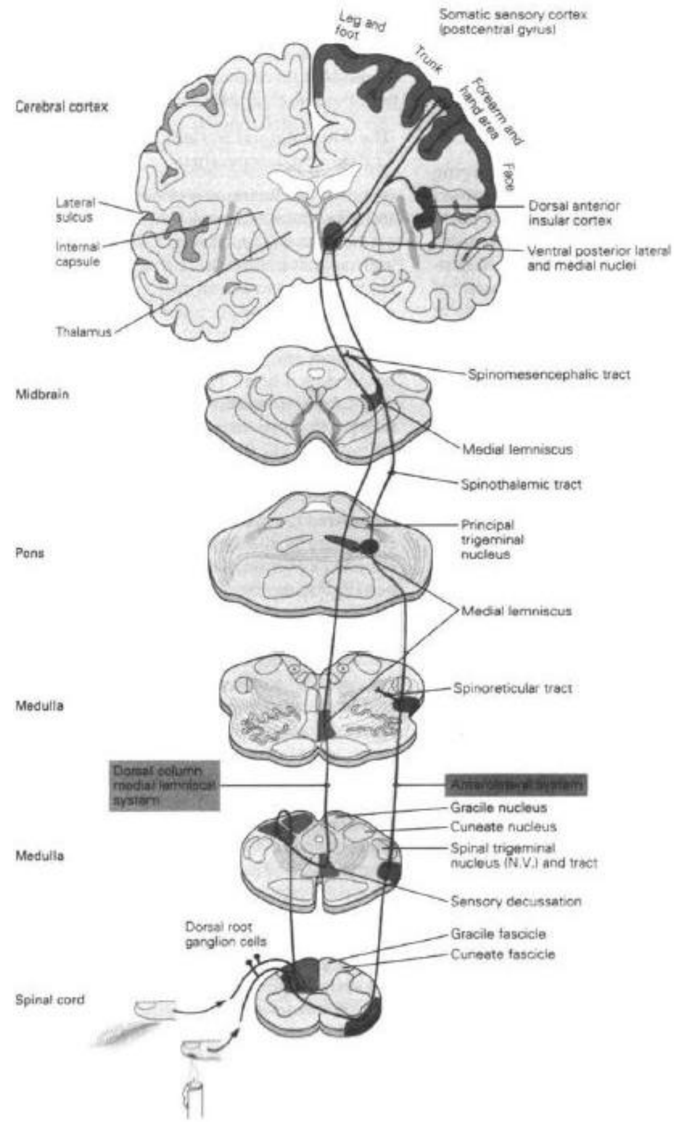


Figure 2-4. Temperature and tactile sensory information transmitted along axons from periphery sensor receptors, through the spinal column and then to the brain. Courtesy of [22].

Axons responsible for sensory and proprioceptive information diverge from those responsible for carrying temperature related information in the spinal column. While the sensory axons are thicker, the temperature axons are thinner and follow a separate pathway through CNS (Figure 2-4) [22]. Not all of the afferent nerve fibres reach the Medulla however, approximately half of them terminate at various spinal levels in what is referred to as propriospinal fibres [23]. The major axonal pathways are then routed into two distinct regions in the upper spinal regions: the gracile fascicle and the cuneate fascicle, and terminate in their respectively named nucleus within the medulla. From there, the neural pathways cross to the opposing side of the brain stem, passing through the thalamus in a nerve bundle known as the medial lemniscus, then routed to the primary somatosensory cortex in the postcentral gyrus of the parietal lobe [24].

2.1.3 The Brain

The average human brain possesses in the order of 10^{11} neurons, with each neuron having an average of 7000 synaptic connections to other neurons, making it the most complex organ found in the body [25]. The neuronal clusters are responsible for monitoring and control, both autonomously and consciously, of all of the body's organs, muscles and functions. Although the operations of the individual brain cells are now understood in considerable detail, the way that they operate in concert is not yet solved [26]. The parietal lobe is the uppermost portion of the CNS and is located at the top of the cerebrum and is divided into two gyrus: the precentral (motor division) and the postcentral (somatosensory division). As shown in Figure 2-5, the portions of the two gyrus responsible for motor and sensory control and feedback are mapped throughout the sub-regions of the two gyrus and are mirrored in terms of bodily region with few exceptions [27]. It is apparent that the highly evolved sophistication of the somatosensory and motor cortices are difficult to reproduce artificially. Further details regarding the brain and its functioning is beyond the context of this document.

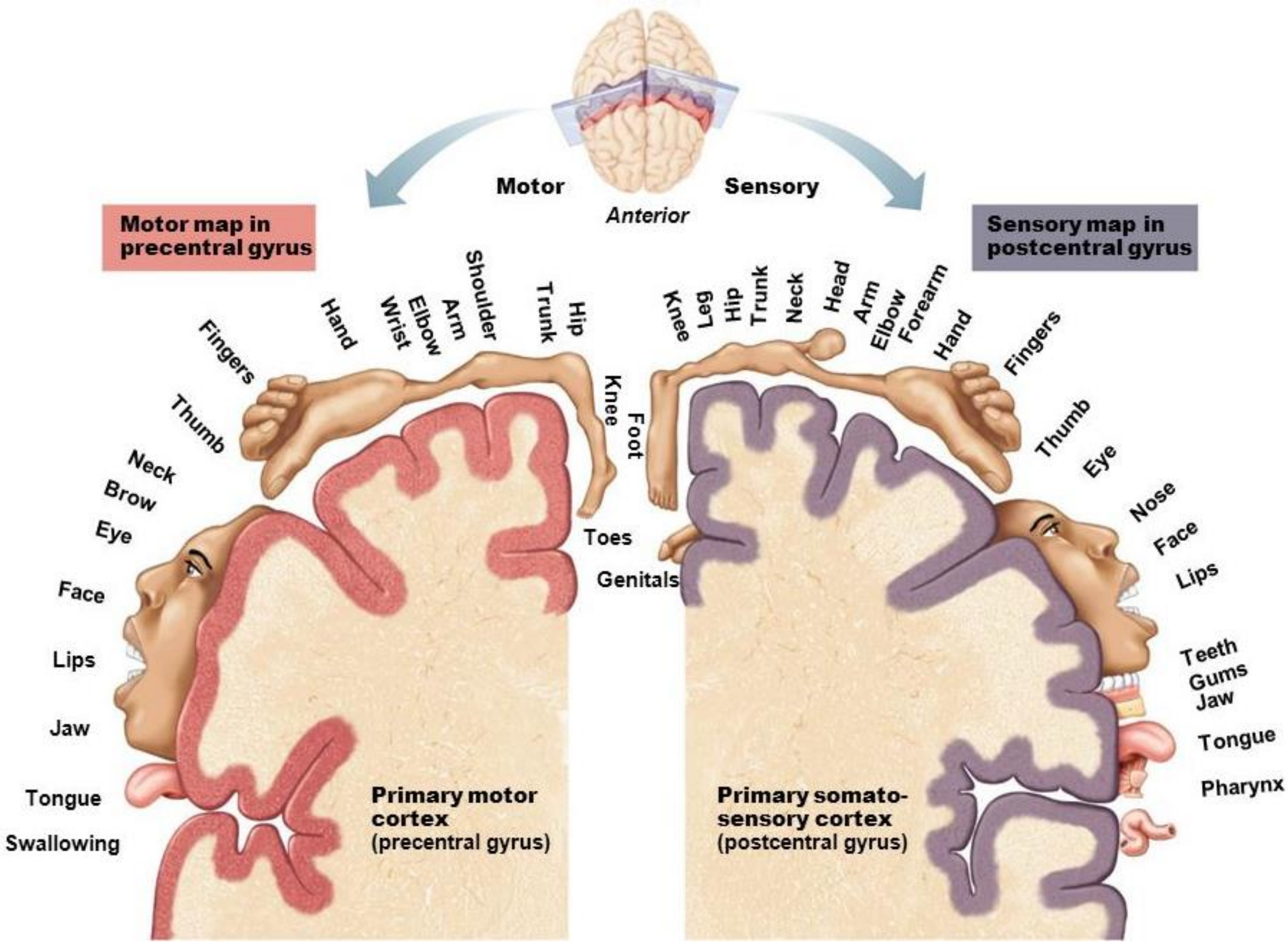


Figure 2-5. Mapping of the motor and somatosensory cortex in the cerebrum. Courtesy of [28].

Now that the biology of the human peripheral sensory system has been explained, it is evident by the micro-scale and amazing functionality that the human body is a marvel of modern evolution. Due to the inherent complexities and miniaturized nature of human somatosensory components, it is extremely difficult for humans to fabricate comparable artificial limbs for those who have lost a limb or were born deficient. The next sub-chapter will discuss the foundational principles of prosthetics.

2.2 Prosthetics

Prosthesis first recorded use dates back to between 3500 and 1800 B.C. with Queen Vishpla of Ancient India being fitted with an iron leg following the amputation a battle wound, enabling her to return to the battlefield [29]. Though the first evidential prosthetic found comes from Ancient Egyptian times (circa 1000-800 B.C.), as an embodied woman's body found in a tomb was adorned with an ornate wooden prosthetic toe on the right foot and showed evidence of wear [30]. Modern history reveals many other notable examples of prosthesis, mainly employed by those who could afford or were adeptly skilled to be capable of crafting such novel devices. These early prosthetic devices highlight that although they were primarily employed as a mechanical aid for those who are missing appendages, prosthetics were also commonly used for cosmetic purposes to disguise missing parts of the body.

As specified in ISO 8549-1:1989(en), a prosthetic device or prosthesis is an "Externally applied device used to replace wholly, or in part, an absent or deficient limb segment. It includes any such device within the human body for structural or functional purposes" [31]. Prosthetic devices may be employed on virtually any part(s) of the body and each device varies in terms of *performance* (weight, capability, etc) as well as *desirability* factors (fit, cosmetic appeal, etc). The higher the level of sophistication and customization of a prosthetic will generally increase its value and also its total cost. Low-cost, prosthetic creating campaigns are becoming a popular way to provide 3D-printed plastic prosthesis to impoverish people who do not have the means or access to more expensive replacement appendages. There exist a wide range of prosthetic devices used for specific individual requirements as well as some general purpose prosthetics meant to appeal to a larger audience of patients. As no literature reference could be found for a general categorization of prosthetic devices, prosthetic device classification table was created from a general overview of observed market prosthesis (Table 2-2).

Prosthesis Classification Level	Description	Usage	Example(s)
Level 0 (Simple)	Prosthesis meant for superficial esthetic replacement.	Cosmetic only. Does not replace structure nor functionality.	Artificial ear, nose, breast, eye.
Level 1 (Basic)	Prosthesis intended to partially restore some of the lost structural or functional requirements. Basic level of prosthetic device control usually absent of tactile feedback.	Day-to-day, low-impact activities of minimal duration, mechanical aid, specific functionality restoration.	Wooden leg, replacement hand hook attachment.
Level 2 (Intermediate)	Prosthesis intended to restore the majority of lost performance, both structural and functional. Moderate level of device control with or without replacement tactile feedback.	Full day use, worn within workplace contexts, allows user sufficient functionality to complete common daily tasks with comparable performance.	Articulated arm/hand used for object manipulation, knee replacement.
Level 3 (Advanced)	Prosthesis intended to fully restore or enhance previous performance. High level of control for intensive or sensitive tasks, may have a heightened level of tactile feedback. Generally non-invasive but may be surgically attached to body or embedded to central nervous system.	High performance contexts, meant to be worn for high intensity activities, may be singularly purposed or meant to replace some feedback and/or functions, may be high performance such as for use in athletic competitions.	Transfemoral ‘blade runner’ leg, myoelectric arm such as the DARPA [32] or Bebionic 3 arm [33], LifeHand2 [34] with implanted electrodes.
Level 4 (Bionic)	Prosthesis that is cosmetically indistinguishable to lost appendage, restores or may enhance performance through high fidelity control, while replacing lost feedback and may provide additional capability.	Permanent replacement of missing appendage affixed /embedded to the human body, extreme contexts or environments, may enhance sensitivity feedback or provide sensations to additional stimuli.	Future developments.

Table 2-2. Classification of prosthetic devices.

The levels of classification in Table 2-2 were derived from a survey of general prosthesis and classification ranges from level 0 to level 4 proportional to the increased structural and functional performance, comprising of both control and feedback factors. Level 0 implies that there is minimal control nor practical functionality required from this type of prosthetic, merely possessing form as well as a cosmetic value. Prosthesis classification levels 1-3 provide a graduated framework for a wide range of prosthetic devices that restore lost performance and various levels of tactile feedback to the user. Finally, the level 4 classification is intended to leave room for ‘over the horizon’ research and development in which prosthetic products can reproduce, and in some cases even provide additional, feedback and control mechanisms to that of a human body's natural appendages.

A functional diagram of a finger prosthesis is provided as an illustrative example in Figure 2-6. Dashed lines represent the varying degrees of control as well as tactile feedback which a prosthesis is capable of delivering to its user. Prostheses classified as a level 0 would be absent of control and feedback, while the prostheses classified at higher levels would include enhanced control and tactile

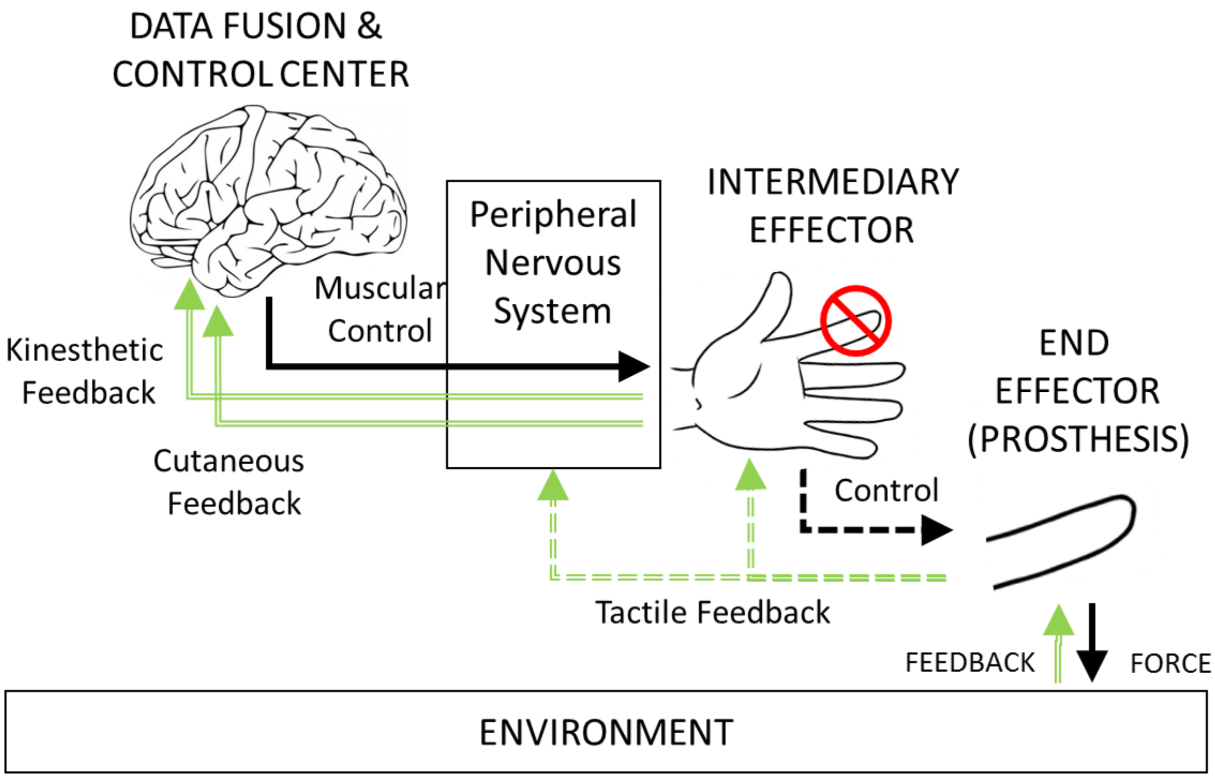


Figure 2-6. Prosthetic finger functional diagram. Dashed lines represent varied levels of control and tactile feedback dependent on prosthesis capability.

feedback. When tactile feedback is provided by a prosthetic device, Sensors in the prosthesis capture environmental feedback that is relayed to the intermediary effector or directly to the peripheral nervous system. The following two sub-chapters will further detail two important aspects of prosthetic devices: Prosthesis control and prosthesis feedback.

2.2.1 Prosthesis Control

Although prosthetic device control is not the primary focus of this thesis, it is unavoidably linked to the performance of a tactile system and therefore merits closer investigation. Just as movements of the human body are controlled by efferent nerve impulse signals originating in the brain and activating muscle groups, a functional prosthetic device requires a manner in which to the user is able to accurately control its movements.

The higher the prosthetic classification level, the more sophisticated its control mechanism and the greater the requirement to control the fidelity of the device. Dexterous manipulation of objects demands a stable means to achieve independent and artificial muscle control, a graduated mechanism to apply the desired level of force, and the ability to affect movements in real-time. The simplest of prosthetic devices (levels 0-1) require little to no control, merely a manner in which to be affixed to its intended location on the body. Mechanical means of control, whether using tendon-driven or muscular actuation, is the most popular choice (levels 1-3) due to its resemblance to the natural form of control. Yet, more novel forms of control such as robotic or myoelectric control mechanisms are becoming increasingly popular in prosthesis of higher classification level (levels 2-4) and offer the user a more intuitive manner to control the device.

Control has dominated the prosthetics research landscape in recent years, with the showcasing of implanted prosthetic devices which are controlled by muscle movements and nerve impulses. A commonly retrieved image is that of a prosthetic hand holding an egg at precisely the force necessary to grasp the egg without crushing it. Manufacturers have seemingly fine-tuned finger force thresholds of these prosthesis to enable slower and more delicate grasping when an object is detected. However, this does not imply that the user of the prosthesis is able to *feel* the precise moment in which to reduce the pressure so as not to crush the eggshell. Rather, in most cases the device has been programmed to limit the force so as to keep the eggshell intact. For a prosthesis to achieve the highest levels of classification according to Table 2-2, user tactile feedback is paramount and will be discussed in the proceeding sub-section.

2.2.2 Prosthesis Feedback

The value of prosthesis is enhanced when it is capable of conveying tactile feedback. At its most basic level, feedback is provided by the transfer of contact force upon the prosthetic to its interface points with the human body. As a prosthesis is normally affixed to the remaining natural parts of the human body using either temporary or permanent means, vibrational patterns may also be transmitted through the prosthesis to the user depending on the properties of the prosthetic device. For instance, an amputee may be capable of detecting higher frequency vibrational patterns using one's natural mechanoreceptors at the prosthesis interface point when employing a rigid plastic prosthetic leg.

More complex devices are capable of translating or integrating additional types of tactile feedback, such as temperature or friction, or employ more sophisticated tactile translation schemes to achieve enhancements to sensory feedback fidelity and dimensionality. Sensory remapping can be simply achieved with a sensory feedback type to feedback dimensionality ratio of 1:1, however other ratios are possible. Sensory feedback and dimensionality will be discussed further in proceeding sub-chapters.

The following sub-chapters will delve into three related subject areas, exploring tactile sensing dimensionality, explaining methods of artificial tactile sensing, and highlighting modern sensory remapping innovations that were studied prior to beginning work in this research area.

2.3 Haptic Perception

Haptic perception is defined as information obtained through environmental interactions and researchers have further subdivided it into two classifications: Cutaneous/Tactile and Kinesthetic [35]. The first domain refers to use of sensory receptors located subcutaneously (within the dermal layers) that provide awareness of stimulation occurring on the outer surface of the body [37]. Kinesthetic perception is the interpretation of information derived from the receptors located in muscles, tendons and joints. Thus, haptic perception "…is the tactual perception in which both cutaneous and kinesthetic systems convey significant information" [35]. Active perception is performed purposefully by the host to explore environmental characteristics, passive perception is where a part of the environment makes coincidental contact with the host [37]. Tactual perception may refer both to **natural** tactual perception, as realised by humans and other living creatures, and to **artificial** tactual perception, as interpreted by

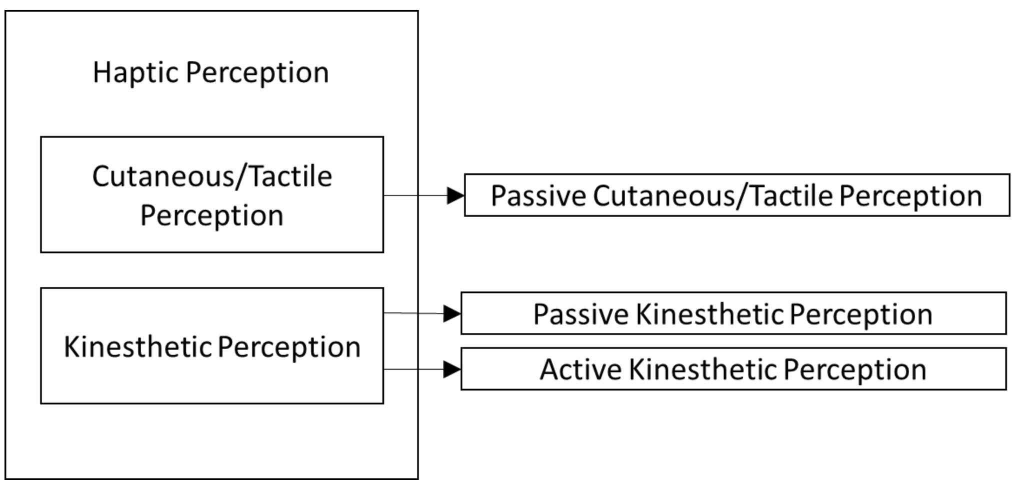


Figure 2-7. Tactual Perception sub-classifications. Adapted from [36].

machines and robots [35][38][5]. Haptic perception is derived from a combination of environmental stimuli, the host's spatial awareness as well as previous haptic experiences.

2.3.1 Tactual Dimensionality

The multi-dimensional nature of tactual perception is an important factor in discriminating between objects found in one's surrounding environment and rivals vision as the most important sense that a human possesses. When attempting to ascertain a mystery object's identity, tactual perception comprises of distinctive, discriminatory sensations that together provide clues regarding the object's identity. For example, shape/size and roughness characterize the geometric and material properties of an object.

A recent survey of 16 historical Psychophysical perceptual studies of the material properties of unidentified objects has revealed deficiencies in the standardization of 'adjective label vocabulary' [39]. The survey concluded that use of a five-dimensional, material-perceptual standard model be adopted which is mediated primarily by the friction dimension: **macro** and **fine roughness**, **warmness** (warm/cold), **hardness** (hard/soft), as well as **friction** (moist/dry and sticky/slippery). It is important to note that the survey was strictly interested in the dimensionality of material-based object tactual perception, completely excluding any geometric-based properties. This work provided insight into the multi-dimensional tactual perception abilities possessed by humans and which tactual dimensions are predominantly employed to discriminate between objects. When considering prosthetic devices as replacements for lost human appendages, the ability of the prosthetic user to perceive these five tactual dimensions should be evaluated.

2.4 Artificial Tactile Sensing

Many artificial means of tactile sensing exist today and an understanding of each type provides insight into the options that could be successfully employed in a prosthetic device or in a robotic implementation. Tactile sensing technologies are classified according to the manner in which transduction occurs: Those that employ mechanical and electrical methods, and those that employ more eccentric transduction methods such as magnetic, optical, etc. [36]. What follows is a description of some of the modern technologies used in artificial tactile sensing.

2.4.1 Types of Tactile Sensors

Electrical & Mechanical Transduction

Resistive tactile sensors use the change in resistivity of a detection material in order to determine contact forces. These sensors are usually constructed using a grid of conductive wires or using two or more parallel sheets with a resistive coating separated by an insulating substance. A voltage differential is then calculated from the input to the output based upon a change in resistance as the contact force is applied to the sensor. This popular technique is used in a variety of force sensing resistor (FSR) technologies and is commonly employed by touch-screen devices to provide two-dimensional coordinate mapping of contact forces [40][41]. Similarly, piezoresistive sensors, whose resistance changes with the application of force, are also popular forms of tactile sensing material. Advantages of resistive tactile sensing technology include relative simplicity, low cost and scalability without increasing complexity. However, the downside of resistive sensors is the power consumption needed to continually scan the resistive surfaces [35].

Capacitive tactile sensors make use of two conductive sheets separated by a flexible dielectric insulator as a means to transduce contact forces. As the sheets are compressed the distance between them is reduced and a greater amount of electrical charge is transferred between the conducting elements. Miniature arrays of capacitive sensors have been developed successfully at the micrometer scale with refresh rates of 20 frames per second [35]. Capacitive tactile sensors are highly sensitive, easy to fabricate and unaffected by temperature variations. However, these sensors are disadvantageous due to stray capacity and hysteresis.

Piezoelectric materials are quite popular in the tactile sensing literature due to their ability to be used both as a sensor and an actuator [35]. These materials generate a charge when a force is applied, and inversely generate a force when voltage is applied, operating on a similar principle to a double layered conductor with a middle dielectric insulating layer except that the mechanical and electrical transduction properties of piezoelectric materials are coupled asymmetrically. In one such implementation, a piezoelectric polymer comprised of a polyvinylidene flouride (PVDF) film and strain gauges are randomly distributed throughout a silicone-based layer, similarly to the skin's randomized distribution of mechanoreceptors [42]. Some of the main advantages of piezoelectric sensors is the flexibility to be used in either a sensor or actuator role, their size and ease of miniaturization, and their pyroelectric properties (able to measure temperature as it creates a charge). However, the challenge then becomes decoupling the thermal and force vectors applied to the sensor to provide accurate separation of data. A further disadvantage is that the charge generated by force decays over time, making it unsuitable for static contact forces [35].

Optical, Magnetic, & Ultrasonic Transduction

Optical tactile sensors comprise of one of two sub-categories: **Extrinsically modified** where a contact object is displaced between the optical emitter and receiver, and **intrinsically modified** in which one of the optical properties (phase, amplitude, polarization) are modified without interrupting the light pathway [43]. Optical fibres have also been trialled extensively as transducers in designing tactile sensor technologies, where light attenuation is caused by micro-bending. Potential benefits of optical tactile sensors include: Immunity to electromagnetic interference, high resolution, and safety. However, optical emission and detection systems tend to be bulkier than their tactile sensing counterparts, even with the great strides in electronic miniaturization over the last decade [35].

Magnetic based-sensors are also possible for use in tactile sensing as seen in [44] among other examples in the literature. In this work, a compliant, hollow, rubber micro-dome is fabricated with a small permanent magnet on the inside of the dome. Deviations in the magnetoresistance caused by displacement are able to be measured along the three axes with great precision. They are also physically robust and have an excellent dynamic range. The obvious drawback with this approach is that a magnetic tactile sensor cannot be used nearby any external magnetic objects without affecting the sensor's response.

Ultrasonic tactile sensors have also been explored, which use a similar principle to that of optical sensors, insomuch as they employ an emitter and receiver to detect changes in the sonic wave due to displacement of a reflective elastic medium [45]. The temporal change in the ultrasonic echo is used to map the medium (usually rubber) being displaced by force vectors and when the echo is received by multiple receivers, it can accurately localize the resulting displacement pattern on the medium's opposing surface. Main benefits of using ultrasonic tactile sensors are the ability to measure a variety of differing tactile characteristics (force, hardness, friction, slip), a fast dynamic response and good force resolution especially when multiple receiver/transmitters are used. A disadvantage of acoustic-based sensors is the use of materials such as lead zirconate titanate and the difficulties with respect to micro circuitry processing [35].

More recently, tactile sensors evolved from being unimodal mostly pressure-sensitive contact imaging devices to becoming more human-like biology-inspired multimodal-sensing devices integrating a variety of transducer technologies embedded in an elastic skin which is a constituent part of the sensing process [46][47][48]. Although there also exist electrorheological and magnetorheological fluid implementations of tactile sensors, where electrical or magnetic changes cause the fluid to become denser (solidified), their practical usage is still under evaluation.

2.4.2 Recording of Tactile Sensor Information

How does one capture a tactile experience so that it may be reproduced? Visual images are readily captured, digitized and stored in various media formats. However, tactile recording is far less mature and poorly standardized than its visual recording counterpart. It appears that this lack of standardization is due to the disaccord in the acceptance of a universal tactile interface. In this sub-section, articles related to the capturing tactile information for reuse are explored.

John Brown [49] reaffirmed the importance of storing and replaying tactile sensory stimuli in an illustrative example. Though guidelines, metrics, and developmental insight is not offered, he describes an elderly widow enjoying holding hands with a lost partner, reliving significant tactile experiences such as stroking the back of a hand and enjoying a hug. Indeed much of today's innovation has evolved to permit the repeated enjoyment of audial and visual moments that have been captured, while relatively few efforts have been invested into preserving tactile experiences. One such innovation is an application that was developed for use on smart phones called *Couple.* The relatively simple application allows remote users to touch the screen on one device and move a visual representation of a finger on another device. When both fingers are pressed in the same location, the phone vibrates and changes colours. He goes on to further describe the importance of tactile sensation technologies for haptic interactions between family members separated by long distances and may only converse with the assistance of remote communication devices.

Several attempts were made in the early 80's through to the 90's to develop tactile displays that would convert speech into tactile stimulations using a device called a *tactile vocoder.* One of the more recent examples describes the development and evaluation of a tactile vocoder by Japanese researchers Wada et al. [50] which using similar equipment to audio recording technologies could have been readily adapted to record and replay tactile sensations. The vocoder interface was a 16 x 4 grid of bimorph piezoelectric actuators on a 30mm x 17mm area that is touched by the user's fingertip with each of the 16 rows resonating independently. The actuators were capable of displacement of over 100μm when voltages of 50V or higher were applied. Results of testing yielded a 55% successful identification rate of 1 vowel and 7 consonants, showing the potential practicality of such a device for humans suffering from hearing loss.

Vishniakou et al. [51] reported a more recent electronic recording of force and pressure using an active matrix sensor array made of transparent zinc oxide thin-file transistors and a tactile feedback display using an array of diaphragm actuators comprising of an interpenetrating polymer elastomer network (IPN). Despite high driving voltages necessary to reproduce an analogue contact force, the resulting replay of touch recorded by a personal computer was possible after its recording. Both sensor and actuator array were comprised of an 8 x 8 grid of sensor/actuator.

In closing, this section has categorized human haptic perception, explored the available, man-made sensor options to transduce contact forces into useable tactile information, and briefly discussed the possibility of recording tactual information in a similar manner to captured images or video. The next section will delve into haptic feedback by detailing the modern means of artificial tactile stimulation.

2.5 Tactile Feedback Interfaces

When designing a prosthetic device that remaps sensations felt by a lost appendage, a non-trivial design consideration is the methodology used to stimulate the replacement region(s) of the body. Devices that induce tactile stimulation are referred to as tactile displays or feedback interfaces [52][53]. This section reports innovations in the field of tactile stimulation and focuses on three most pervasive mechanisms: actuation, electro-tactile stimulation, and vibro-tactile stimulation as well as touching upon some novel display devices that covey sensations of temperature, stretch, and friction [54].

2.5.1 Skin Indentation through Actuation

In order to relay contact forces received from a sensor to another part of the body, a form of tactile stimulation is required. The most apparent form of reproducing contact forces is the generation of a linear array or grid of moveable actuators that generates a mechanical stimulus. Actuation can derive its energy from several sources, used to drive the actuators. Ideally, the actuation amplitude is reproducible, has a high refresh rate, low energy consumption, and actuators can be driven individually to create differing spatial sensations. Many forms of mechanical actuation have been conceived, such as: pneumatic and fluidic, electrical and electromagnetic, acoustic, piezoelectric, electroactive polymers (EAP), and shape memory alloys (SMA) [55].

Pneumatic/Fluidic Actuation

Pneumatic and fluidic actuation involves a medium, air or liquid respectively, being physically displaced or modified such that it actuates the end effector of a tactile interface unit. Generally, an air pressure differential within separated and valve controlled tubular chambers is used for pneumatic actuation [56]. Fluidic implementations employ liquids which expand/contract in response to thermal-optical stimulus, such as the 'smart hydrogel' [57] and fluidic chamber amplification techniques that use minimal pressure to create a large displacement of fluid into a flexible micro-membrane [58]. Micro arrays are possible with pneumatic/fluidic tactile display realizations, however most implementations require some additional components to drive the actuation mechanism which lead to greater overall space requirements.

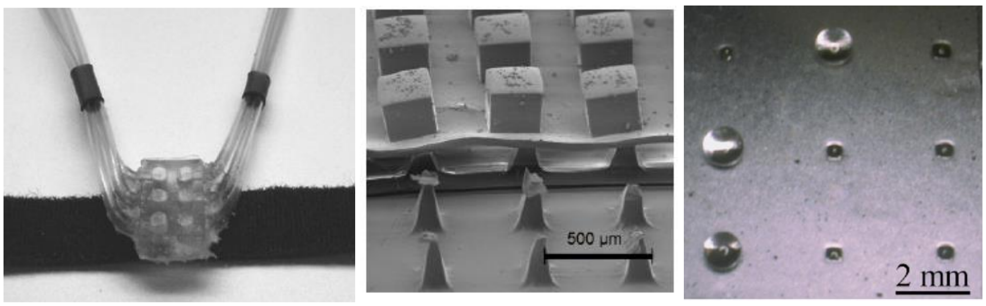


Figure 2-8. Examples of pneumatic and fluidic tactile actuators. **Left:** A pneumatic actuator with flexible coating placed upon the fingertip with Velcro strapping, courtesy of [56]. **Centre:** A ‘smart hydrogel’ tactile display, in which each micro actuator expands/contracts based upon optical/thermal activation, courtesy of [57]. **Right:** A fluidic 3x3 actuator using glycerin encapsulated within a flexible, balloon-like micro-membrane representing the letter ‘s’ in Braille, courtesy of [58].

2.5.2 Electromagnetic Actuation

The main principle behind electromagnetic actuation is that electronic components cause a change in electrical or magnetic properties leading to mechanical displacement. An early attempt of this type was able to create an 8x8 tactile array that within a 1 square inch area as detailed in [59]. As electrical components are readily miniaturized and can operate at high speeds, they are frequently used in tactile displays. Another such actuation is through the use of an electrically activated copper coil in combination with a moveable permanent magnet core as shown in Figure 2-9. The change in magnetic flux caused by increasing electric current through the copper wires opposes permanent magnet’s polarity and magnetic field, thereby displacing the core perpendicularly to the flow of current [60]. Other such implementations were employed as mechanically resistive cues in virtual reality environments [61], using tele-manipulation [47], and creating miniature linear tactile arrays using circuit boards, as in [62].

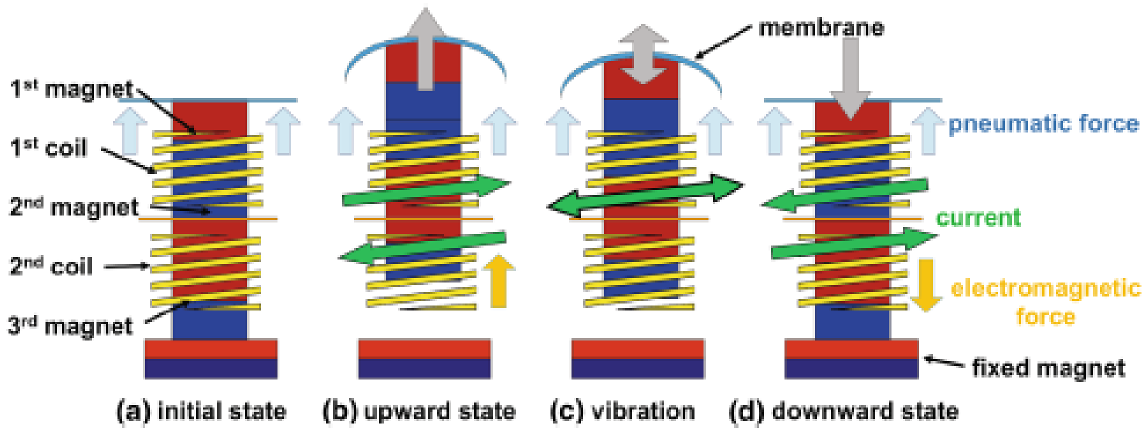


Figure 2-9. Electromagnetic actuation through the use of a changing electric current in copper coils with a moveable permanent magnetic core. The change in magnetic flux due to current in the coils oppose/agree with the polarity of the permanent magnet, thereby causing displacement and/or vibrational patterns against a flexible membrane. Courtesy of [60]. Pneumatic force and an additional fixed magnet were also used in this implementation for precision actuator control.

2.5.3 Acoustic Actuation

Using a novel approach to transduce acoustic propagation through a substrate, surface acoustic waves (SAW) have been demonstrated to elicit sensations similar to kinetic motion through modification of the frequency and frictional patterns. In [63], researchers created a prototype that induces acoustical effects via a medium to portions of the glabrous skin in contact with the presentation area (Figure 2-10).

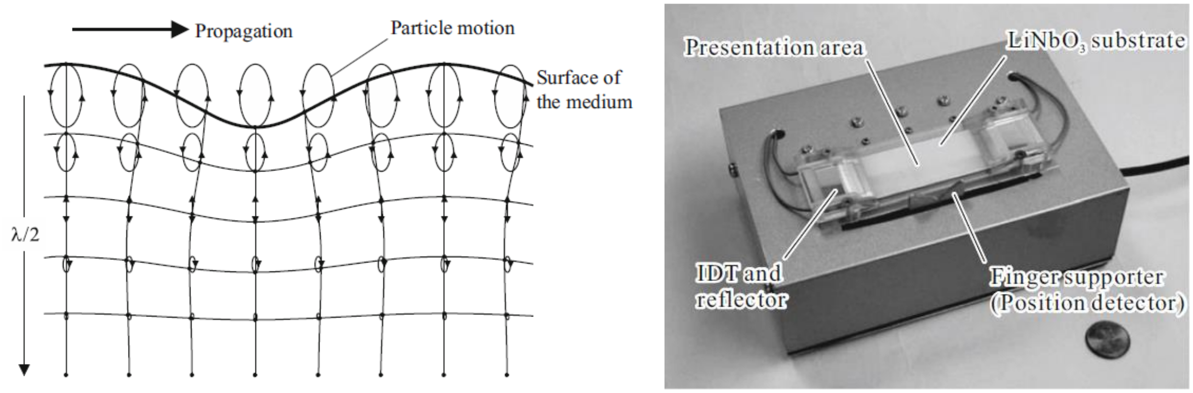


Figure 2-10. Working principle (left) and prototype (right) of a surface acoustic wave (SAW) actuator used to create a sensation of movement and friction shift when in contact with the skin. Right Courtesy of [63].

2.5.4 Piezoelectric Actuation

Another type of actuation that has already been covered in the previous section is the use of piezoelectric materials to generate stimulatory displacement through modifications to the electrical driving signal. “When strain induced by stress is applied to a piezoelectric material, an electric charge appears on its surface (piezoelectric effect)…when an electric field is applied to the same material…results in the deformation of the solid…” [64]. Piezoelectric actuation is currently employed in commercially available Braille readers intended for people with visual impairment.

2.5.5 Actuation using Electromechanically Active Polymers (EAP) and Dielectric Elastomer Actuators (DEA)

Relatively recent discoveries in new materials has allowed for new novel forms of electrically driven actuation. One such group of material that has potential for use in miniature actuation devices is electromechanically active polymers (EAP) and are divided into two sub-groups: Ionic EAP and Electronic EAP, for which the second category is of greater interest to micro-actuation and tactile display technologies. The main difference between the two sub-groups consists of how the polymers are electrically activated, whether through ionic flow of a solute, or use of directed electricity. The activation causes a mechanical displacement of the EAP. According to Runyan and Carpi, EAP technology has matured significantly over the last 30 years and is beginning to reach a level of maturity that is suitable for integration into tactile applications such as Braille actuators [64]. Despite the extensive technical requirements for a Braille tactile interface and the high voltages required to actuate the EAP, it is possible that some commercial products may become available in tactile markets in coming years.

One specific subset of EAP that is of great interest to the haptic research community due to its compact size, electrical efficiency, and ease of manufacturing is the Dielectric Elastomer Actuator (DEA). Actuation of DEA is similar to that of a two-plate capacitor, where voltage differential causes lateral displacement. When combined with a rigid container, the displacement of the DEA can be channeled in

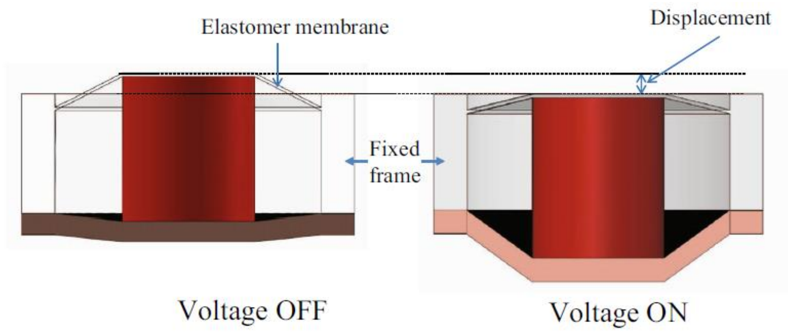


Figure 2-11. Operating state of a Dielectric Elastomer Actuator (DEA) surrounded by a rigid cylinder and framed with soft silicone, causing indirect contact with the skin through the silicone wall. Courtesy of [65].

a particular direction. As with one such application by Phang et al. [65] in 2015, a silicone outer shell was also added to the DEA coupled with the rigid, cylindrical container to cause a gentle actuation. This particular design actuates away from the intended skin contact area when voltages in the kilovolt range are applied as indicated in Figure 2-11. The size of this actuator is quite small, 3mm x 3mm, but remains a few orders of magnitude away from attaining the sensory capabilities of the average human fingertip.

Similarly, DEAs can also be used to displace an independent Braille head tip that comes into contact with the skin. The head tip can be made significantly smaller than the expansion chamber for the DEA, improving miniaturization of actuator contact area (Figure 2-12). One such implementation was created by Di Spigna et al. in 2010. [66] A drawback of this

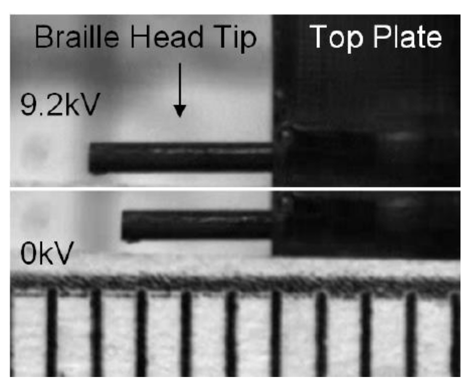


Figure 2-12. Dielectric Elastomer Actuator (DEA) fibre Braille dot technology, actuation of 0.75mm @ 9.2kV, Courtesy of [66].

implementation was that though the head tip contacting the skin was small, the overall size of the chamber still needed to be accounted for in the overall design, requiring a similar amount of space and high voltages to that of other DEA tactile implementations.

2.5.6 Shape Memory Alloy (SMA) Actuation

Shape Memory Alloys (SMA) are a lesser known technology that have the potential for use in tactile applications. The working principal behind SMA is that a coiled wire will expand when thermally activated after applying an electric current to it.

One such implementation by Matsunaga et al. [67], shown in Figure 2-13, employs two SMA coils to move independently controlled pin caps in opposing directions uses a permanent magnet to latch the cap position when stationary. A 10 x 10 grid was successfully prototyped and tested, with pins 2.5mm spacing, a maximum displacement of 2mm, and a refresh rate of 300ms. The assembled pin display prototype occupied a volume of 50mm x 50mm x 90mm (height) and was a significant achievement using SMA due to its small form factor.

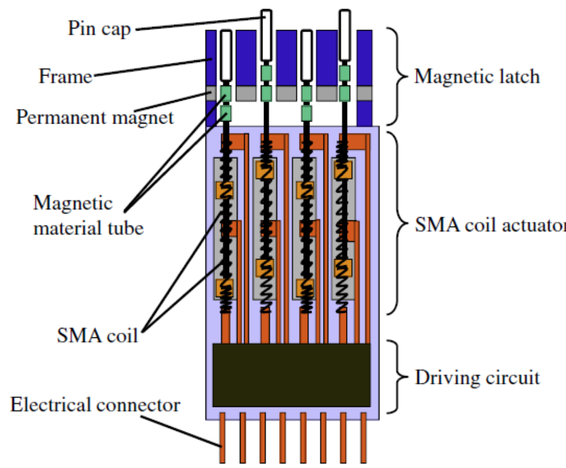


Figure 2-13. Two Shape Memory Alloy (SMA) coils actuate each pin cap on an array, Courtesy of [67].

2.5.7 Vibro-tactile Stimulation

While conducting this research, vibro-tactile stimulation was found to be the most popular method of conveying sensory information to the human body. Due to the pervasiveness of linear resonant actuators (LRA) and similar micro-electronics, these types of devices offer compact and affordable vibratory stimulus that can be actuated with mere micro-amperes. Note that this class of stimulation is distinct from linear actuators which are capable of inducing vibrations through high frequency actuation in that the vibration is driven by the mechanical displacement of an electro-magnet and spring embedded within a metal, puck shaped container. One of the main disadvantages of this type of stimulation is that certain vibrational motors have a relatively poor temporal responsiveness (several microseconds) as the LRA's internal magnet inertia must be overcome in order to achieve a desired frequency. Despite this inherent disadvantage, this type of stimulation is the most commonly employed and widespread tactile feedback mechanism and is employed in mobile phones, gaming controllers, in force feedback equipment used for virtual reality environments, and in many other electronic devices.

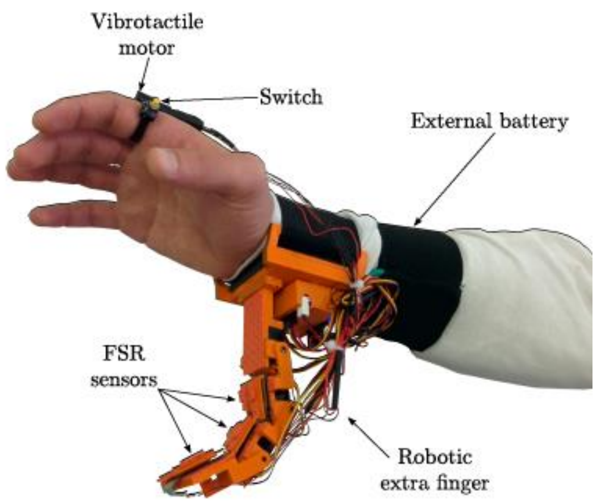


Figure 2-14. Manually controlled robotic finger conveying vibro-tactile feedback to user, Courtesy of [68].

As an illustrative example of vibro-tactile feedback, recent research [68] supplemented the human hand with an additional robotic finger which could convey tactile data to the back of the wearer's hand. The additional robotic finger was manually controlled using a switch mounted on the user's index finger and the feedback was delivered through the use of a vibro-motor embedded in a ring interface worn upon the same index finger, see Figure 2-14. Results revealed that haptic feedback significantly improved the performance in task execution in terms of task completion time, exerted force, and perceived effectiveness. These findings support the idea that tactile feedback increases overall tactile dexterity performance.

Choi and Kuchenbecker [69] adeptly explain the inherent duplicity of vibrotactile displays for haptic feedback systems. Though the low-cost and easily embedded actuators present a convenient tactile feedback option, they are also the most commonly misused tactile technology. The researchers point out that when including vibrotactile actuators in a feedback system, consideration of two main factors must be carefully weighed: the type of vibrotactile actuator to be employed, and the spatial arrangement of said actuator. These two main factors will have a significant impact on the performance and viability of the system, explain the authors.

2.5.8 Electro-tactile Stimulation

Electro-tactile displays employ small electrical currents delivered from electrodes to activate sensory nerves under the skin (electrocutaneous). Since this is a more invasive means of stimulation than some already described, in that electricity is being passed through parts of the body, a great deal of care must be taken to prevent excessively high currents from causing discomfort and or pain. Electro-therapy has long since been used in the medical profession to treat a wide array of psychological disorders and neurophysiological impairments. However, this section will primarily focus upon the small cutaneous activation currents that allow users to perceive electrical sensations that assist with tactile-based dexterous manipulation operations.

Stimulation using electrical current between skin surface electrodes poses both spatial and temporal application difficulties. Namely, the resistance of the skin varies according to many skin surface factors such as sweat or perspiration level, mechanoreceptor density, and differences in tissue thickness. One attempt to adjust current levels depending on these variable factors was made by researchers [70] who introduced a real-time, electrical impedance feedback loop into their electro-tactile display. Using a multi-pulse waveform with corresponding measurement and feedback control, the researchers were able to predict threshold currents required for absolute skin stimulation under differing skin impedance conditions. This is a promising step towards stricter controls for electro-tactile feedback applications, ensuring a more pleasant experience for users.

Later experiments using prototypes by the same researcher, H. Kajimoto, 6 years after the above paper was published showed progress in the area of electro-tactile stimulation [71]. Initially using a vibrotactile stimulator in the first prototype, the second prototype employed electro-tactile stimulation due to the reportedly higher resolution. Images on a tablet were converted into electrical impulses that were broadcast to arrays of skin surface electrode pairs, or pins, that were felt by users. The more mature interface was a 63-pin index finger, electro-tactile actuator that allowed users to recognize relatively complex alphabetic shapes on a tablet. Researchers identified a steep learning curve with the prototype, but the overall outcome was a success: to identify the letters with relatively good accuracy. There is great potential for electro-tactile applications in a future filled with touch screen devices and many of the applications to this type of tactile stimulation will likely become more apparent when more research and safety measures are instituted.

2.5.9 Conveyance of Temperature, Stretch, & Friction

In order to truly physically interact with one's surrounding environment, the tactile sense must be employed, thereby revealing the importance of the tactile sense and tactile stimulation. Though several types of mechanoreceptor stimulation have been explored in this paper, a human being's tactile abilities extend beyond that of the limited resolution of these actuator types. This section will explore less common, artificial actuation studies that complement areas of the tactual spectrum which have to this point have been neglected.

Thermal feedback and multimodality are two of three 'under-researched' features of haptic feedback, according to French researcher Simone Gallo [72]. She states in her research that "…haptic perception results from the integration of multiple somatosensory inputs…" and that "thermal feedback is an ideal candidate…" to investigate interactions between haptic modalities [72]. Presenting a very thorough PhD thesis, she investigates the multi-modal and thermal aspects of the tactile sense in Cartesian fashion. Using a series of thermal-tactile prototypes that employ a thermos-electric device called a Peltier Tile, her research concludes that subjects are able to distinguish thermal differences above 13.3°C with a 0.4mm gap and that the miniature prototype created warrants greater investigation for use in commercial haptic interfaces. The thesis also suggests that for haptic interfaces to become more pervasive, the devices must become less rigid in form and more miniaturized to garner widespread appeal.

Investigations into skin stretch, its perceptual impact, and its possible application areas have been explored. Bark et al. [73] examined a wearable haptic display for motion that uses rotational skin stretch upon hairy skin surfaces. In an isolated context, subjects were able to discriminate between different rotational displacements of skin stretch within two to five degrees. Whereas in a more 'realistic' setting, subjects used feedback to control the positioning of an object in virtual reality to within six degrees of the range of motion. The study highlights that hairy skin can be artificially stimulated with a user capable of detecting limb or joint rotation using robotic or prosthetic devices and the potential to make use of lower density mechanoreceptor parts of the skin's surface to relay tactile information.

Variations in surface friction levels are increasingly being studied as an alternative to electro and vibrotactile feedback. Janko et al. [74] designed several textured surfaces and analyzed the frictional forces and their relation to object geometry and contact parameters. A finger sliding on a textured surface was used to derive contact forces between the varying textural patterns and the results suggested that force production is not limited to surface geometry and contact parameters. This implied that there is much greater complexity surrounding the perceptual challenges regarding active touch sensing of a textured surface.

Not surprisingly, Disney researchers have also invested significant resources into haptic interface devices, seeking more immersive sensory experiences for their park visitors. One study in particular examined the use of a friction display that can modify the perceived strength of friction as a function of the applied voltage as a user moves a finger across an image [75]. In this way, the image surface deviations can be felt as a frictional differential, with changes in image depth being perceived as increased/decreased friction on the touch screen's surface. It may not be long before additional tactile experiences are realised due to the recent innovations in haptic interfaces.

In summary, there exist multiple tactile feedback means and methods on the open market. Though examples of tactile feedback exist in the literature and reveal enhanced performance using a supplementary appendage, this work will focus upon the improvement of prosthetic devices through the provision of artificially induced feedback relays. Using a variety of the aforementioned technologies, a prototype will be developed to assist those who have been a victim of dismemberment and consequently lost their natural biomechanoreceptors.

CHAPTER 3 – TACTILE ENABLED PROSTHETIC FINGER

A prototype tactile enabled prosthetic finger was developed using a combination of tactile sensors as well as select actuators previously described in Chapter 2. This chapter will outline the history and rationale behind the design of such a multi-purpose prototype. It begins by providing a thorough examination of the foundational characteristics of an ideal system, then highlights key trade-offs that were weighed in the prototype's development such as the selection of materials and design choices, finishing with a summary of the prototype's expected experimental results.

3.1 Background

The development of any system requires careful consideration of both direct and indirect factors which affect the system's performance. A wide range of tactile feedback systems could have been developed that addressed the needs of amputees, of those who remotely control dexterous service robots, or provide feedback in virtual reality contexts. The scope and purpose of each tactile feedback system is unique to the problem that it was created to overcome and thus a specific issue was selected to advance within this vast research field.

The prototype described herein was originally conceived to provide replacement tactile feedback for an individual who had been a victim of a single finger amputation. The accompanying loss of hundreds of mechanoreceptors, thermoreceptors, and free nerve endings found within a human's fingertip represents a significant tactile perception divestment. Thus, the primary objective of the prototype was to restore lost fingertip's sensory abilities by remapping the missing appendage's sensory feedback to another part of the body. In this case, a synthetic fingertip with embedded sensors was to be fabricated that would allow an artificial finger to detect minute mechanical and thermal variations and consequently activate actuators on a remaining body part, thereby allowing a user to perceive, or feel, changes to the synthetic fingertip. Secondary and tertiary objectives of the prototype would include tactile feedback for non-amputees in both remotely-controlled, robotic dexterous operations as well as immersive tactile feedback for virtual reality contexts. These main objectives are summarized in Table 3-1.

Prototype Objective (PO)	Description	Supported Thesis Contribution(s)
PO1	Remap lost sensory abilities to another part of the body	C1, C2a, C3, & C4
PO2	Tactile feedback for remote control robots	C2b, C2c, C3, & C4
PO3	Tactile feedback for immersive virtual reality contexts	C3 & C4

Table 3-1. Principle objective descriptions for the tactile prototype. Thesis Contributions as per Chapter 1.

The prototype will serve as a use case to validate the hypothesis presented earlier: *Tactile feedback rendering significantly increases a subject's ability to perform dexterous manipulation tasks.*

3.2 Prototype Development

The creation of the tactile feedback prototype followed a systematic sequential development strategy, comprising of three distinct stages. The first stage was the conceptualization of characteristics which underpinned a successfully functioning product, accompanied by a thorough scan of academic articles, commercially available products, as well as emerging innovations. The second stage consisted of taking the ideal characteristic traits from the first stage and designing a system which would meet the research objectives. Finally, the last stage saw to the acquisition and assembly of a functional prototype that could be used in tactile experiments. A description of each stage is detailed below.

3.2.1 Conceptualization Stage

During the prototype conceptualization stage, prior to the design and construction phases, a preliminary conceptual diagram, or strategic view, was created to focus prototyping efforts. The general concept of the prototype was to remap tactile sensory inputs of either prosthetic appendages or remote robotic dactyls to the user's hand. A glove was envisioned as a suitable platform to host the tactile feedback module, which would act as a tactile actuator, relaying the sensations realised by the prosthetic or robotic fingertips. Possible application areas included dexterous manipulation in many domains including, but not limited to: robotic surgery, prosthetic feedback, and immersive virtual reality. The initial conceptual diagram is depicted below in Figure 3-1.

Figure 3-1. Conceptual diagram (Strategic View - 1 or SV-1) of the tactile feedback prototype.

Ideal characteristics of a tactile feedback system were then postulated based upon the lessons identified while researching various related works in tandem with existing commercially available products. Several competing characteristics were taken into account during the planning and development of the tactile feedback system and are enumerated in Table 3-2. Relative scoring was subjectively assigned to underscore the importance of the characteristic with regards to fulfilment of its main purpose: the remapping of the fingertip's biosensors.

Characteristic	Description	Importance
Latency	Time delay between sensor reception and stimulus actuation should be minimized so as to relay near real-time information.	HIGH
Accuracy	Does the system readily convey identifiable tactile information and have a high degree of realism? Are the perceived sensations naturally understandable? Are the artificially actuated sensations similar to sensations that would be felt with natural biosensors?	HIGH
Usability	Includes mobility, comfort, aesthetic value, training time, and durability sub-characteristics. Can the system be used independently of a fixed location? Is it waterproof? Does the user want to wear and use it as it provides value without extensive training?	MODERATE
Form Factor	Size, shape, and weight sub-characteristics. Is the tactile system light enough to be easily employed? Is it bulky or restrictive to common user movements?	MODERATE
Cost	How expensive is the system to produce (time, funding, resources)?	LOW
Power use	Does the system require a large amount of power to be usable?	MODERATE
Invasiveness	Does the system require surgery before use or is the system worn on the surface of the body?	MODERATE

Table 3-2. Characteristics of the proposed prosthetic tactile feedback system.

The latency characteristic was rated the highest importance for a prosthetic application. This is because latency between sensor activation and the corresponding relay to the tactile actuator introduces time synchronization issues to the user of the prosthetic. Should a delay be significant enough between a user's action and the feedback received from the system, users would have an unfavourable experience similar to that of a fragmented telephone conversation with another person with a communication delay of greater than 1000ms. Though it is possible for a tactile feedback system could be implemented with an extremely small latency, in the order of a several microseconds, it is imperative that said system's latency be below the maximum perceivable delay threshold (60ms) [76]. Ideally, latency should be minimized so as to yield a near real-time relay of tactile feedback to the user.

Accuracy of a tactile feedback system was rated to be of high importance. The characteristic of accuracy is defined as how closely the artificially generated feedback resembles expected sensations felt when employing one's own natural tactile biosensors. Otherwise stated, the intuitiveness, or ease of understanding of the feedback received from the tactile system, is a qualitative representation of the system's accuracy. A high level of intuitiveness when using a tactile feedback system equates to reduced device training time, as the feedback received is similar to what is expected when using one's natural biofeedback sensory system. Accuracy is vitally important to a tactile feedback system in order to properly represent the tactile information in a meaningful way that the user may already be familiar.

Usability represents the durability, employability, esthetics, and comfort of the tactile feedback system. Rated as having moderate importance, the usability characteristic encompasses features that are representative of a user's willingness of make use of the system in a variety of contexts. Thus this characteristic is a balance of qualitative and quantitative factors, with measures stemming from both subjective (e.g. comfort) and objective (e.g. mean time between failure) criterion.

Should the tactile feedback system be overly cumbersome or restrict natural movement, it is likely to sit on the shelf and not be used. The form factor characteristic measures the value of the tactile feedback system from a user perspective in terms of: size, weight, shape, and freedom of movement. Although the form factor characteristic is related to traits found within the usability characteristic, it is distinctive due to its more quantitative sub-characteristics.

A characteristic that should be included in every system design is cost. Though the cost characteristic was rated as low in terms of overall system importance, the amount of resources expended to create the tactile system cannot be ignored. Just as there are limited resources available to every researcher, so does proper accounting for materials, financing, and work need to be considered.

Power use is an expression of the amount of energy required to operate the prosthetic tactile feedback system as well as the number of types of energy required to fuel the system. Systems that consume less power are of greater value than those with greater power consumption, just as systems with fewer types of power are less complex than those requiring more power types. Additionally, should a system be capable of harvesting energy and storing the energy for future use it would significantly increase its overall value. This characteristic is rated as moderately important for the development of a prototype.

With many modern innovations requiring a single or recurring surgical procedure for implanted medical devices, invasiveness is also a characteristic that was considered to be part of a prosthetic feedback system. The less invasive that the tactile feedback system was to its user, the more desirable it was for users. This is not to say that all non-invasive tactile feedback systems are superior in performance or comfort than a more invasive system. Rather, non-invasiveness commonly reflects a wider general appeal and is rated as having moderate importance in the design of a tactile feedback system.

Having conceptualized an overarching framework with key characteristics that would steer prototype development and design stages, the following step was to determine tangible design guidelines for a prosthetic tactile feedback system that would bring concept to reality.

3.2.2 Design Stage

In this stage, the foundational principles of the system's design were considered and solidified. Distilling the overall design of a prosthetic tactile feedback system into manageable parts was accomplished through the generation of core design decisions which were deeply rooted in the prioritized characteristics derived during conceptualization. What follows in this sub-section is a description of the core design principles that led to the selection of materials and acquisition or required parts to realise a functional, tactile-feedback prototype.

Design Consideration #1 (DC1): Types of tactile feedback & sensitivity. Human fingers are endowed with thousands of mechanoreceptors, thermoreceptors, and free nerve endings connected to a branched network of afferent nerves permitting near real-time relay of tactile information through the peripheral nervous system to the brain. Replicating such an amazingly sophisticated system using artificial materials was a very daunting endeavour to say the least. Therefore, realising a more feasible prototype that can perform basic tactile feedback functionality was foreseen. The first aspect that was considered was that the prototype was to be 'sensationally deterministic' meaning that it had the ability to distinguish between variations in stimulus. From a study of the literature, the following tactile feedback stimulus types were forecast to be relayed using the tactile feedback module and corresponding artificial sensors: *temperature*, *friction*, *pressure*, *force*, and *vibration*. Sensors would have to be sufficiently sensitive to register variations in each type of stimulus, and actuators would have to have a wide enough range to appropriately convey the variations to the part of the body being actuated.

DC2: Control & dexterity. Whether using prosthetic or robotic fingers, a suitable control mechanism is required so as to allow for both kinesthetic manipulation and unhindered natural freedom of motion. Evidently, for a user to be capable of active touch exploration and dexterity, the control of the fingers is arguably one of the more important aspects of the design. Suitable control of the artificial fingers should allow the device's user the ability to touch, to grasp, and to move objects. In order to be capable of such dexterous manipulation, it is foreseen that the system will require a minimum of three fingers. Methods for controlling the fingers vary widely from simple mechanical or fluidic control (prosthetic fingers) to more sophisticated means such as remote, electronic control (robotic fingers). As the focus of this dissertation was on tactile feedback, it was preferred to derive a suitable control mechanism that was simple to implement and provided the appropriate level of control and dexterity needed to pursue the feedback objectives. The usage of passive components and materials was also to be maximized so as to reduce controlled-finger energy requirements.

DC3: Placement & platform. The tactile sensors will clearly be placed in the prosthetic and robotic fingers, however the tactile feedback module, which comprises of the various artificial actuators to convey tactile sensations to the body, could be placed in a variety of different locations. Intuitively, the closer the tactile module is to the part of the body that would normally receive feedback, the faster the user would adapt to where the feedback was coming from. In this case, the proximal and most familiar placement of the actuators was instinctively on the hand which had undergone finger amputation. The specific part of the hand remained an open question. As glabrous skin on the palm of the hand tended to have a greater concentration of bio-receptors than did hairy skin, the most favourable location for the tactile feedback module was the palmar region of the hand. However, actuators placed on the palmar side could potentially interfere or obstruct the natural mechanoreceptors used for object manipulation actions. Therefore, the specific location of tactile feedback was a balance between risking sensory confusion amongst the more commonly used mechanoreceptors on the palmar side of the hand, and potentially losing sensitivity range on the dorsal side of the hand on regions of hairy skin that were not as well endowed with high concentrations of receptors. With respect to the platform that would hold the tactile feedback module and a prosthetic finger, a glove was seemingly the best solution for stability, comfort, and real estate for this purpose.

DC4: Miscellaneous design notes. Due to the pervasiveness of modern day electronics it was decided to incorporate electrical components into the prototype design as a wide variety of electronic circuitry, sensors, and prototyping materials were readily available through online retailers. The only drawback with using electrical components was that some form of electrical energy was therefore required in order to provide power to the electrical components. As mobility of the system was also important to the overall design, battery power would need to be mounted upon the glove to enable ‘cordless’ operation. It was also decided that the prototype would attempt to make use of modular design components to enhance versatility as well as expandability with the prototype’s wide array of potential applications. For example, a similar actuator set on the glove would be used for either prosthetic or robotic finger feedback, simply using the respective sensor module corresponding to the user’s needs.

Another design consideration was to create a functional prototype that had some semblance to natural tissues and appendages on the human body. Care was to be taken to use bio-compatible materials that were both texturally and esthetically comparable to the missing finger where possible. Robustness and usability in a variety of environmental situations was also considered at this stage, but instead of investing a great deal of time into ‘hardening’ of the device it was decided to first focus efforts toward the development of a functional tactile feedback prototype. What followed was a search for suitable materials that fulfilled the aforementioned design considerations.

3.2.3 Procurement & Sub-System Testing Stage

Armed with the theory, the concepts, and the design principles, it was time to start shopping for prototype solutions. This section will cover the steps undertaken to acquire materials, to research viable techniques, to test sub-components, and to construct the tactile feedback prototype. Initially, selection of suitable parts will be discussed and later towards the end of the section, a more detailed description of the prototype complete with diagrams and images will be provided.

Glove selection

A sturdy, semi-rigid, and comfortable platform needed to be selected to which the tactile feedback module and prosthetic finger would be secured. After visiting some local merchants, the glove shown in Figure 3-2 was selected based upon its suitability for housing the electronic components, while providing a modest amount of rigidity, and offer comfort to the user with the added weight of the future electronics that comprise the tactile feedback module. A fingerless glove was selected, as a prosthetic finger could be added to any of the holes depending on the needs of the amputee. Another feature of the glove was that it had a double layered fabric, allowing for actuators to be embedded close to the skin in between the fabric layers.

Figure 3-2. Chosen glove for prototype: Mechanix Wear Tactical M-Pact Fingerless Covert Glove.

Prosthetic Finger

From a general review of the literature, there has been an expanded interest in soft robotics, which seeks to exploit electronics that are embedded or encased in softer materials such as silicone, rubber, resin, or similar flexible gel-like substances. Since the prototype would likely use electronic materials, it would follow that to provide an esthetically and texturally comparable compound to skin could possibly be used to construct a prosthetic fingertip with embedded sensors. Though several of the compounds researched were difficult to obtain in Canada, a two-part, rubber-like compound which could be used for the prototype was located from a commercial supplier. The chosen product was a two-part, urethane rubber compound called *Vytaflex®* and is manufactured by a company called **Smooth-on** (www.smooth-on.com) which is available in various consistency levels when cured. The product comes with two bottles, each containing a separate aqueous solution, one containing a clear glue like substance which hardens when exposed to air and the other filled with a transparent, copper coloured rubber solution. When equal proportions of each solution are mixed together, then poured into a mold and left to cure for 16 hours, it creates a flexible, semi-transparent, pinkish brown, rubberized solid. *Vytaflex® 20* was deemed a suitable hardness for the prosthetic fingertip application due to its similarity to the density of soft tissues.

Creating a mold for the *Vytaflex®* was the next order of business. A great prototyping tool that is becoming more and more widely available is the 3D printer, which turns and electronically generated Computer Assisted Design (CAD) model into a real-world, plastic model in three dimensions. Having one in the laboratory provided me an excuse to test its potential by generating molds for the rubber compound. Three different fingertip sizes were created out of ABS plastic using a 3D printer and corresponding CAD designs in order to trial the various fingertip sizes with the embedded electronic sensors. When the plastic molds came out of the printer, by chance there were micro layers of thin plastic filament which served well as fingerprints for the prosthetic rubber tip.

A *prosthetic finger* also needed to be chosen for which a fingertip embedded with sensors could be fashioned. An online search for a simple, mechanically controlled finger was undertaken. One particular design caught my attention as the majority of it was also fabricated using a 3D printer: The Knick Finger, shown in Figure 3-3. An Australian entrepreneur (Nick) who had been a victim of dismemberment at the intersection of the intermediate and proximal phalanges of his index finger on his left hand developed the prosthetic and shared his creation under the creative commons licence for public, non-commercial use. The actuation of the artificial finger is caused by curling action which causes

Figure 3-3. The Knick Finger: A mechanically-controlled, 3D-printed prosthetic finger, Courtesy of [77].

tension upon the steel wire anchored to a wristlet. This amazing prosthetic was well engineered by its designer and the fingertip could be easily replaced to suit our prototype's purpose making it an excellent candidate for future use. Further details regarding the Knick Finger can be found at reference [77].

Tactile Sensors

Several types of sensors were discussed earlier in chapter 2.2 that could be used as artificial mechanoreceptors in the fingertip of a prosthetic finger. Mechanical force, temperature, as well as vibrational patterns were the target sensations that were attempting to be detected. Thus the sensor selection would ultimately be focused upon these three primary detectable sensations.

First *addressing mechanical force*, force sensing resistors (FSR) were a natural choice due to their relatively small scale, high sensitivity, and low cost & power consumption. An interesting alternative to FSR was a product called a *'thin pot'* or potentiometer, in essence a linear FSR, as resistance values varied linearly with the location of the force along an axis perpendicular to the sensor. The thin potentiometer did have one disadvantage, in that it had three input/output prongs compared to the FSR which only had two prongs thus requiring less wiring. The three prongs of the thin potentiometer required connection to ground, 5V, and the potentiometer value wire, respectively. The FSR only required a 5V input and the second wire was the output value. The chosen sensor, shown in Figure 3-4, was Interlink Electronics FSR 400 with solder tabs (www.iefsr.com) and the thin potentiometer used was the Spectrasymbol® TSP-L-0012-103-3%-ST.

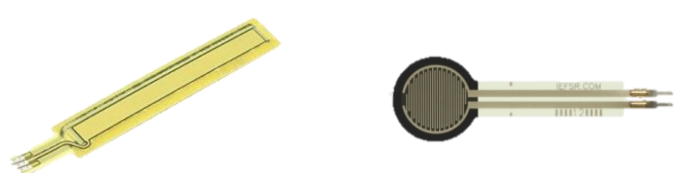


Figure 3-4. Thin potentiometer (left) and a Force Sensing Resistor (right) two mechanical force sensors used for artificial

The FSR 400 was preferable as the threshold actuation force was as low as 0.1N and its sensitivity range extended to 20N, making it sensitive to small exerted force. The thin potentiometer required a force of

0.7-2.2N to actuate and its value would change depending on the force location thereby making it feasible for a user to detect exact position when combined with an actuating technology.

There were a wide variety of *vibration sensors* available on the market, but the majority of vibrational sensor applications were for wake up detection for car alarms, for knock sensors in cars which help diagnose engine misfires, as well as shut off threshold detectors in washing machines and kettles. The vibrational sensor comprised of a thin strip of piezoelectric material that generated a charge differential when flexed and thus created a voltage differential causing current flow. An added circular weight could also be attached at the strip's tip would induce a resonant frequency upon the sensor, enabling the sensor to generate a greater voltage differential when the corresponding vibrational pattern is detected. I was interested in seeing if this technology could also be used to detect and relay subtle vibrational patterns of human touch when embedded within a prosthetic fingertip. Thus, a MEAS a Parallax MSI Peizo File Vibra Tab sensor, shown in Figure 3.5, (www.meas-spec.com) was used.

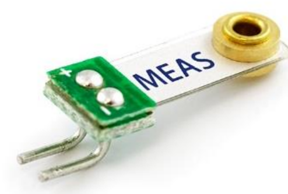


Figure 3-5. Piezoelectric vibration sensor used in the prototype sensor array.

A *temperature sensor* was foreseen to be placed within the artificially created fingertip so that thermal activity could also be detected. As our natural fingers readily detect temperature variations, it seemed only natural that a replacement finger would need a form of thermal detection. We selected the the more compact sensor DALLAS Systems DS18B20+, shown in Figure 3-6, that allows for 1-wire parasitic power and reading. Resolution of this temperature sensor was reasonably high (0.0625°C) and would allow for accuracy of thermal gradient of less than a tenth of a degree Celsius. It was also postulated to use an additional sensor close to the thermoelectric tile as a thermal safeguard, or

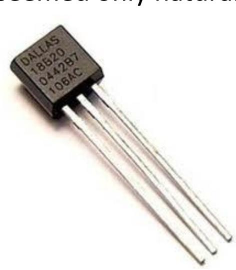


Figure 3-6. Temperature sensor: DS18B20+ with a resolution of 0.0625°C.

possibly embed more temperature sensors to allow for a global temperature average and local thermal readings at other parts of the hand.

Actuators for Tactile Feedback

For a user of the tactile prototype to be capable of feeling the information captured by the sensors embedded in the prosthetic fingertip (or a robotic fingertip for that matter), there needs to be one or several actuators able to convey the sensations in an understandable form. Actuator technologies were explored in Chapter 2.3 and this section will explain the rationale for chosen actuators for the prototype. Of the many actuation options available for use, four types of sensations required to be transmitted to the user from the chosen sensors: thermal, force, vibration, and location.

A thermoelectric tile, also called a Peltier tile, is a two-sided, square tile that generates *thermal feedback* when electrical current is applied. The thermoelectric phenomena arises from an intercoupled electrical and thermal current in a material. This particular tile is constructed using multiple n-type and p-type thermo-elements connected in electrical series, with all thermal elements in parallel between heat source (one side) and heat sink (other side). Thus, the tile can either generate a thermal differential by applying an electrical current *or* generate an open circuit, electrical current when a temperature differential is applied to opposing sides of the tile itself. The open circuit voltage generated from a temperature differential across the thermoelectric module is a function of the temperature gradient, ΔT, the number of thermo-elements connected in series, j, and a material constant called the Seebeck coefficient, S. Assuming that both n-type and p-type thermo-elements have the alike thermal and electrical properties, then the open circuit voltage may be expressed as:

$$Voc = j \times S \times \Delta T$$

It should also be noted that the above equation is ideal and does not account for the thermal resistances of the heat source and heat sink. Therefore, the open circuit voltage will always be less than ideal due to these unaccounted thermal resistances. Quite a remarkable technology indeed and its applications include refrigeration, air conditioning, and energy harvesting with new innovations, such as a thermoelectric tile powered flashlight, being found and is displayed in Figure 3-7. [78] As thermoelectric tiles came in a variety of size and maximum power ratings, it was foreseen that a suitable tile would be employed to covey thermal information to users of the tactile feedback glove.

Figure 3-7. Thermoelectric tile (Peltier tile).

Force feedback was arguably the most important aspect of the tactile feedback module. Linear Resonant Actuators (LRA), shown in Figure 3-8, are comprised of a moving magnetic disk encapsulated within a larger metal frame and stimulated with electrical current. This generates a vibration that can be felt when placed against the skin. These affordable, simple, and easy-to-use vibro-electric devices are available in many sizes and were a possible solution for the tactile feedback module. The resonating frequency was also easily adjustable by modifying the input voltage, thereby providing an additional form of actuator dimensionality to the user. It was thus decided to employ separate LRA for all of the input sensors (force, vibration, and pressure).

Figure 3-8. Linear Resonant Actuator (LRA).

Testing of the Sub-systems

Several of the electronic sub-systems needed to be wired, programmed, tested, and configured prior to creating an integrated module. The tactile system was broken down into the following sub-systems: thermal feedback (temp. sensor & thermoelectric tile), vibrational feedback (vibration sensor &

LRA), pressure feedback (FSR & LRA), and location feedback (Thin potentiometer & LRA). A description of each sub-system and an account of some of the hurdles overcome during this stage will be covered in the next few paragraphs. Though a functional prosthetic fingertip with sensors enclosed within a rubber composite mold had not been poured to this point, it was decided to test each sub-system using the individual components in order to reduce uncertainty and validate a proof-of-concept for each part of the overall design.

The *thermal feedback module*, comprised of a thermoelectric tile and temperature sensor would be used to provide the user with thermal sensory information detected from the prosthetic fingertip and conveyed to an area on the back of the gloved hand. The temperature sensor had three metal pins on it, but when employed in 1-pin, parasitic power mode, is capable of operating with a singular powered wire with the remaining two pins tied to ground.

One major drawback of this particular temperature sensor was that it required a minimum of 750ms of idle time for the temperature to be converted into a readable format for the microcontroller. In combination with the two additional commands that needed to be sent to the sensor for it to activate, this meant that the temperature could only be read once every second. Although this one second delay was acceptable for this tactile prototype's purposes, it made programming quite a challenge since the microcontroller uses a continuous *while* loop in its execution. Further, a strong pullup resistor (4.7kΩ) was required between the bus and the 5V pin in order for the sensor to draw sufficient power during the 750ms conversion period. Thanks to several public internet posts on how to work around programming pitfalls, most notably from Simon Tuchev (see [79], [80], & [81]), a workable solution was implemented and the temperature sensor provided a reading to the microcontroller.

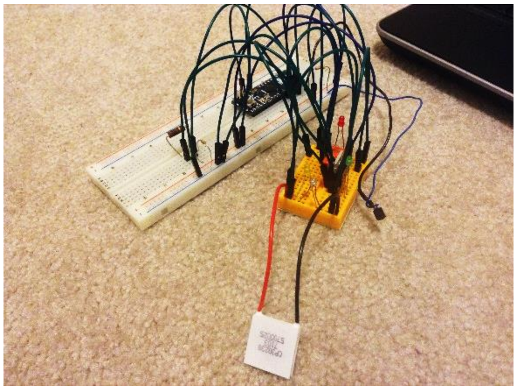


Figure 3-9.Thermal Feedback System validation with thermoelectric tile (bottom) and temperature sensor (centre right). Tile was correctly activated when a temperature differential of more than one degree Celsius was detected within a period of 1 second.

The thermoelectric tile produced a temperature differential when electrical current was applied, but it too required some engineering to make it work in a desirable manner. Since it was intended to use the same tile for both hot and cold temperature feedback types to the user, there had to be a mechanism to reverse the current flow in order to generate either hot or cold sensation on the side of the tile directly in contact with the user's skin. Additionally, it was found that the high current draw from the thermoelectric tile was causing the microcontroller to reset due to insufficient power when plugged into the computer or a battery. Thus alternative options for powering the microcontroller and tile separately as shown in Figure 3-9. After a great deal of research, I came across a MOSFET regulator combined with a Double Pole Double Throw (DPDT) relay hardware solution that permitted drawing current from a separate battery source from that of the microcontroller. The MOSFET served as an electronically activated, variable current regulator allowing more precise control over the current flow to the thermoelectric tile. I am very grateful to the following public internet sites for sharing their wiring diagrams and code to assist me in producing a reversible thermoelectric tile solution for this tactile feedback prototype (see [82],[83], & [84]).

Vibrational feedback was configured and wired for testing and proved to be a very sensitive sensor. The MEAS vibration sensor yielded a surprising amount of charge differential for even the minutest amount of strain applied. However, the voltage differential generated was sufficiently high to potentially cause damage to the microcontroller (as high as 15V was observed). So the addition of a high impedance resistor (1MΩ) was necessarily placed between the sensor and the controller in order to limit the voltage. Sampling was done at 100Hz and the voltage differential detected was supplied with alternating current, thereby inducing both negative and positive voltages. Interesting to note that the sensor itself required no electrical power to operate. A great advantage with piezoelectric materials is their ability to generate their own charge differentials when strain is induced. This sensor would therefore later be trialed within the prosthetic fingertip and it was hoped that in combination with a suitable actuator, would assist users to detect the specific texture of materials from their signature vibratory and frictional characteristics.

Pressure feedback was designed to be detected using the miniature FSR sensor within the artificial fingertip and rendered using the vibrational intensity of an LRA. As only one FSR sensor was available, it was foreseen to create a single prosthetic finger with multiple sensors (temperature, vibrational, FSR, and Thin potentiometer) to determine the capacity of the relatively small fingertip volume given the great number of sensors. It was also envisioned that as multiple LRA were being used as actuators in the glove, the user may have some difficulty in interpreting the tactile feedback from each specific sensors. Therefore, adequate spacing and placement of the LRA would be of critical importance to counterbalance any potential confusion from the perceived feedback.

After years and years of becoming accustomed to one's mechanoreceptors during childhood, it is possible for a human to distinguish the relative location of mechanical force exerted upon one's body. As the density of mechanoreceptors is high on the palmar area of the human hand, humans are able to distinguish with fine precision the location of an induced force upon a fingertip. This precise sensory ability to identify location, combined with additional sensory feedback cues, may be how humans are capable of such dexterous manipulation tasks. The use of the thin potentiometer sensors in a prosthetic finger is a possible way to enable such dexterity in amputees. Therefore, several thin potentiometer sensors were wired, configured, and tested in order to fulfil this objective of increased dexterity. As the resistance of the thin potentiometer was linearly dependent on the location of the force exerted over the length of the strip, it was foreseen that a user would be capable of determining exact fingertip *force location* based upon the variable feedback intensity of the LRA, as shown in Figure 3-10.

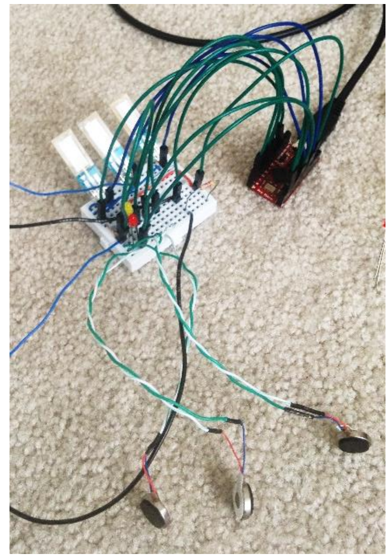


Figure 3-10. Location Feedback System validation with three linear thin pot sensors (top) and three LRA actuators (bottom).

The software for each of the feedback module sub-systems was developed using the Arduino programming suite. A very simple program was written in a C++ compatible programming language which contained an initial setup section used to configure the microcontroller pins, and a repeatable loop section that would execute indefinitely until the microcontroller was turned off or lost power (Figure 3-11). The majority of the input pins used for each sensor were analogue with the exception of the temperature sensor which used a one wire digital bus for operation. The analogue input pins detected voltage at stepped intervals of 4.9mV and returned a value of 0-1023 which was then converted to a usable number range depending on its application. Analogue output pins were also employed to actuate the LRA and thermoelectric tile, and values between 0-255 could be sent using a pulse width modulation scheme to the output pins in order to control the LRA as well as the thermoelectric tile output power. As

```
Setup Microcontroller
Setup Display
Loop
    Read Sensor Data
    Map Sensor Data to Actuator Power Levels
    Write Mapped Data to Actuators
    Display Data
Repeat Loop
```

Figure 3-11. High level software routine.

the code for separate sub-systems were progressively integrated into one program, an initial software release entitled "Pro Micro / Tactile Feedback Module Test Code Prototype v1.0" was finalized. Code for the tactile feedback system can be found at *Appendix E*.

3.2.4 Prototype Integration & Construction Stage

Once all sub-systems had been validated independently, it was time to build all of the sub-systems onto a glove-mountable circuit board and embed the actuators at strategic locations within the glove as shown in Figure 3-12. Wiring of the circuit board and interconnectivity to the fingers were also considered. This section will describe the steps undertaken to create the first tactile feedback module prototype that would be used for experimentation purposes.

Figure 3-12. Embedding the actuators between the fabric layers of the glove.

The first part of the construction was to determine and affix the actuators to the glove. As the glove had a dual fabric layer, it was possible to carefully make small incisions within the material of the glove and slide both LRA and thermoelectric tile actuators between the fabric layers. Initial positioning of the LRA and the Peltier tile were on the back of the right hand, as indicated in Figure 3-13 and were chosen based upon a maximum dispersion to avoid user actuator confusion. The right hand was selected due to the predominance of right-handedness in society implying that finer control was capable with the more frequently used hand. Once the actuators were sewn into location, construction then turned to the circuity board that would house the hardware necessary to operate the tactile feedback system.

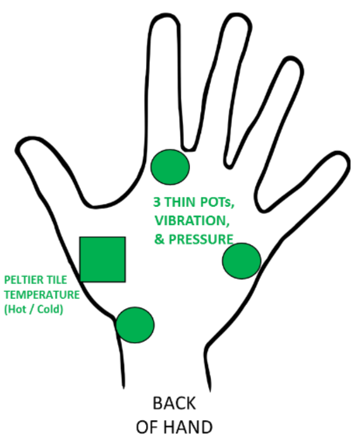


Figure 3-13. Placement of actuators in prototype v1.0 glove.

The circuit board was an etched board with copper rows and columns configured to enable rapid prototyping of electronic circuitry, as displayed in Figure 3-14. Two LED lights were initially added to indicate that the thermoelectric tile was been activated (red) and the directionality of the relay, showing the direction of current flow to the tile (green). Two further enhancements were made to the initial system configuration due to the limited troubleshooting ability of the system during construction: (i) the addition of a monochromatic display, and (ii) a CAT-5 port that was to be used to connect the remote sensor module from the fingertip by simply plugging the cable into the outlet (Figure 3-15). An overall wiring diagram was then created and is shown in Figure 3-16.

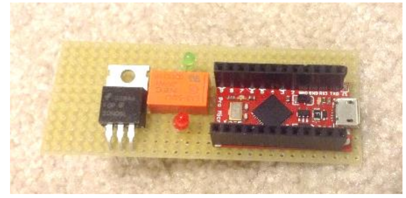


Figure 3-14. Circuit board with five soldered components (left to right): MOSFET, DPDT relay, two LEDs (green & red), and the Pro Micro Microcontroller.

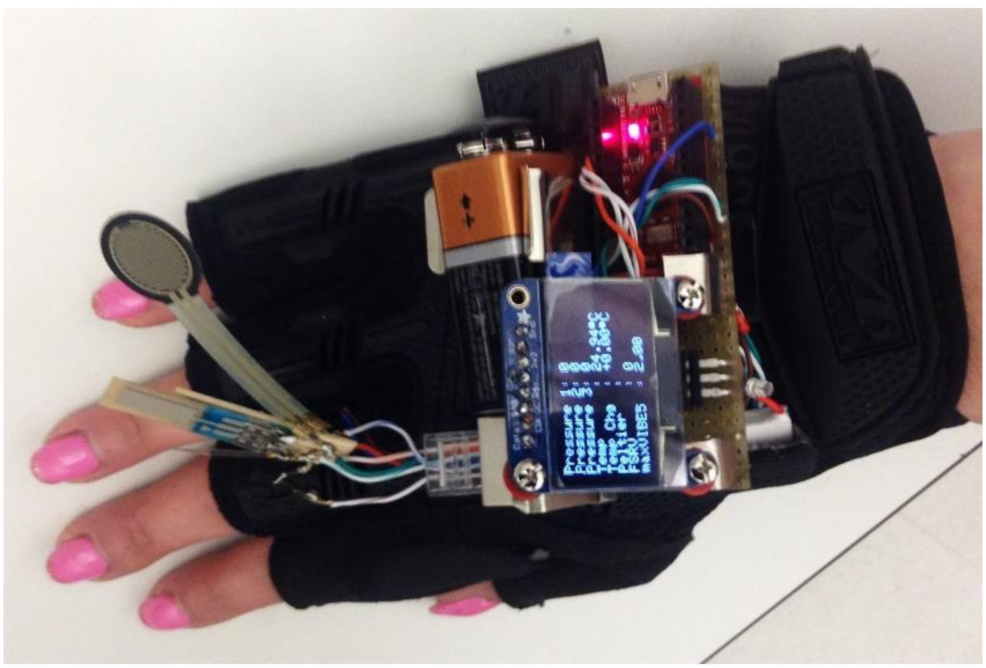


Figure 3-15. Photo showing the initially constructed glove with a sensor 'test' module attached to the CAT-6e port.

Construction continued with the mounting of a battery holder and a standard 9V rectangular battery selected due to its ability to supply the thermoelectric tile. All available I/O pins were being used

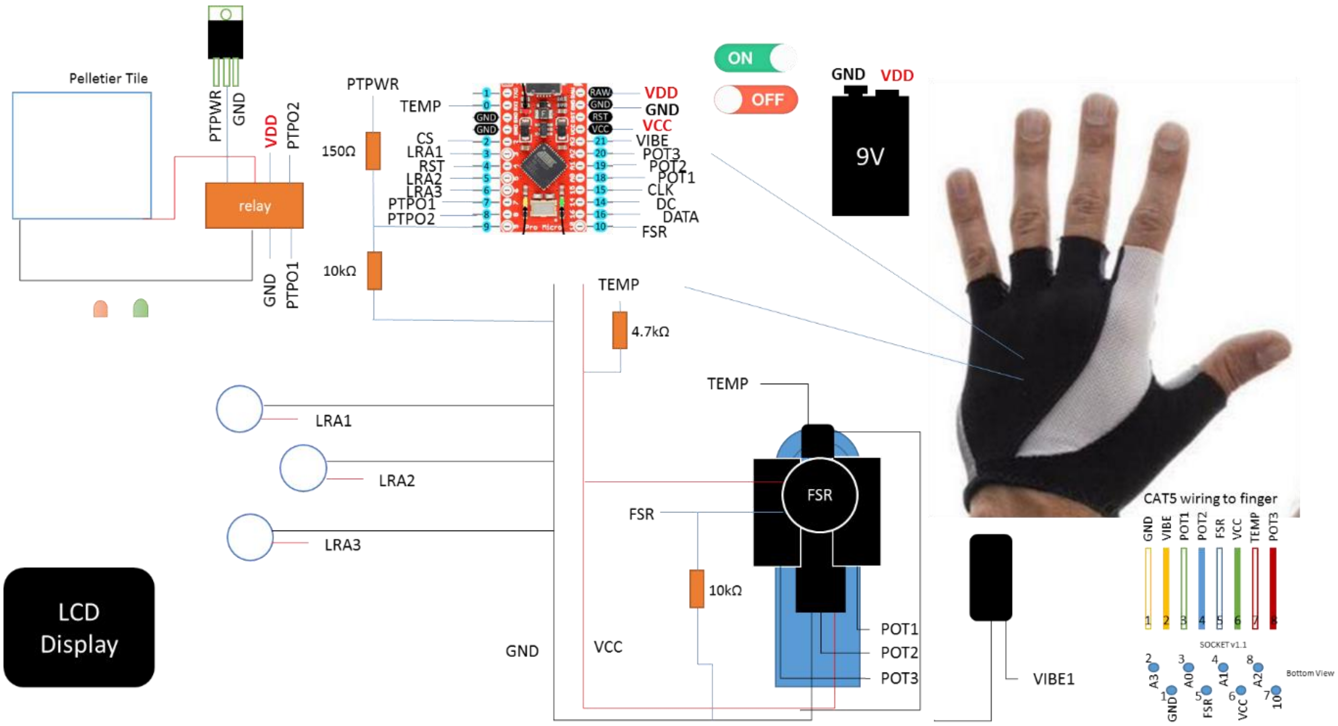


Figure 3-16. Preliminary wiring diagram for the construction of the initial prototype tactile feedback system.

on the microcontroller and it was clear that additional capacity would be needed if the number of sensors were to change.

During the initial prototype, it was envisioned to embed all of the six sensors in a single artificial fingertip (Figure 3-17). It was discovered that there was insufficient space within the fingertip to house all of the six sensors. Therefore, the density of sensors was reduced in the single artificial fingertip and the sensors were distributed to two additional fingertips as it was foreseen that blindfolded active touch experiments may be impossible to achieve with a single finger used for exploratory tactile sensing. A more realistic active touch methodology would be required, with the addition of supplementary artificial fingertips to permit active/exploratory tactile experimentation.

At this early stage of construction, the experimentation plan was already being conceived. Realizing that it would be difficult to recruit multiple subjects who have identical, index finger amputations, it was admitted that experimentation with five-fingered subjects was inevitable. Therefore, in order to allow experiments without having to make drastic modifications to the prosthetic finger location, it was decided to make a version of the glove which would not change with each subject that participated in the experiments. The problem then became: how does one create a tactile prosthetic feedback prototype without cutting off subject's fingers? After much thought, two possible solutions came to mind. Either robotic fingers would need to be used with a suitable control mechanism employed so as not to interfere with the main purpose of the thesis (tactile feedback), or prosthetic fingers would need to be created and affixed to natural fingers while masking the subject's natural mechanoreceptors. As no robotic hand had been tested for use to this point, it was decided to make use of the human body's instinctive control mechanism and secure the prosthetic fingers to the user's existing natural fingers.

Efforts were then shifted away from equipping amputees with a singular prosthetic finger to instead determining a suitable manner in which to secure multiple artificial appendages to subjects who have all of their natural fingers. The main focus of the experiments were indeed the tactile feedback patterns to the user, and the control mechanism was but one indirectly related parameter. It was conceived that prosthetic finger attachments were to be affixed to a user's natural fingers, in order to instinctively control the artificial

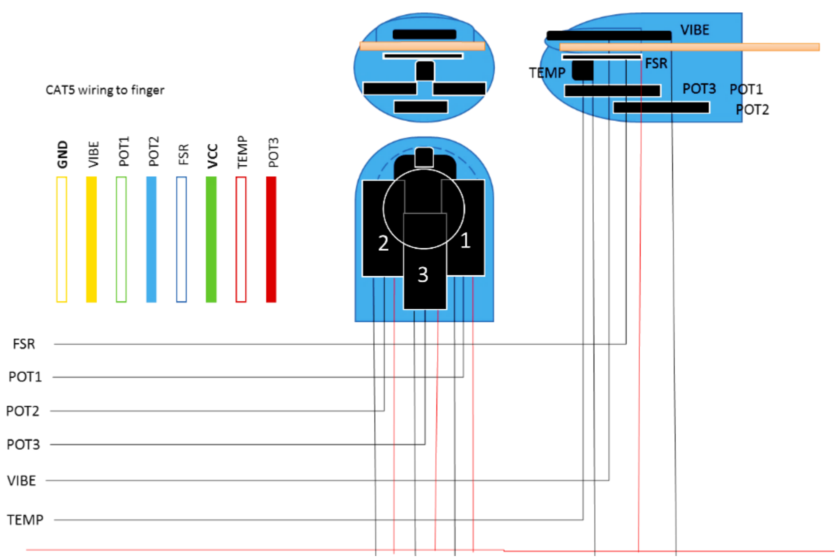


Figure 3-17. Schematic of the initial artificial fingertip with 6 embedded sensors.

appendages that would serve to mask each user’s natural tactile senses. Wooden sticks, albeit not the most elegant nor sophisticated solution, offered a semi-rigid yet easily configurable prosthetic finger platform on which to attach sensors and cure a rubber fingertip upon.

The first artificial fingertip created was packed with sensors: 3 thin potentiometers, 1 temperature sensor, 1 FSR, and 1 vibration sensor, as shown in Figures 3-17 and 3-18. Six sensors carefully placed upon the wooden crafting stick was then inverted into a 3D printed mold. Once the

Figure 3-18. Production steps for creation of the initial artificial fingertip with embedded sensors and rubber casing. 6 sensors were attached to the wooden craft stick (top left), then inverted into a mold in which the rubber compound was poured and left to cure overnight (top right), finished product ready for use by connecting 45cm long, CAT-5 cable to the circuit board sensor input port (bottom left & right).

rubber had become firm, the fingertip was removed from the mold and the orange-coloured, semi-transparent rubber provided a protective shell around the sensors which held them securely suspended within the semi-solid material. A CAT-5 cable of 45cm length was spliced and soldered onto the sensors according to the initial wiring diagram, thereby ensuring modular connectivity between fingertip sensors and main circuit board.

3.2.5 Prototype v1.0

The Tactile Feedback Glove prototype v1.0 consisted of a feedback glove (Figure 3-15) in concert with the initial artificial fingertip with 6 embedded sensors (Figure 3-18). Although the software sequencing remained unchanged as shown in Figure 3-11, the software thresholds and mapping for each of the four sensor types were refined in order to provide the preferred sensor sensitivity ranges, tolerance values, and actuator intensity.

Control of the artificial finger was initially performed using natural fingers from the opposing hand and moving the sensor-laden fingertip over a variety of textured surfaces (table top, wood, rubber, fabric, sandpaper, etc) while the feedback was being provided to the glove worn by the user. Several software changes were made to compensate for a lack of feedback sensitivity when the artificial finger was depressed against surfaces. Sensitivity increases were possible, however when the sensitivity of the microcontroller pin was enhanced past a certain level, electronic noise would cause the actuators to be stimulated randomly, causing great user confusion.

It should be noted at this point that all of the sensors were placed as close to the surface of the rubber fingertip as possible. This was done intentionally so as to minimize force, pressure, vibrational, and thermal distortion through the rubber to each respective sensor. Inevitably, the rubber casing insulated the true values of the stimuli presented to the fingertip, and in some cases completely obscured any reading at all. For example, the vibration sensor failed to provide meaningful material texture information as intended, becoming stimulated only when the fingertip was hit very hard upon a

Observation	Impact	Recommendation
Sensor sensitivity was distorted by rubber thickness	Sensors had reduced ability to detect exerted stimulus	Place sensors as close to fingertip surface as possible; embed dense medium between surface and sensor
Rubber layer wore down with repeated use	Rubber protective coating would peel, leaving sensor exposed	Use a rubber compound that was more firm, or increase rubber thickness
Microcontroller mini-USB port snapped off due to excessive cable strain	Microcontroller could no longer be connected to computer, rendering it non-programmable	Reposition microcontroller to reduce cable strain or create wireless solution
A single, artificial finger is insufficient to conduct active touch, tactile exploration	Amount of tactile feedback is limited	Make more artificial fingertips, 3 in total so that user can manipulate objects
Microcontroller I/O pins have all been used with the single artificial fingertip sensor array	The current microcontroller cannot support additional sensors for more fingers	Increase I/O pins through use of the Genunio Microcontroller; spread the existing sensors to two additional artificial fingers
Feedback from vibrating LRA was overwhelming and caused vibrational saturation of gloved hand	User could no longer identify specific types of feedback as hand was becoming numb from the constantly vibrating LRA	Examine alternative LRA vibrational patterns that employ a reduced amount of vibration; alter placement of LRA to allow user to better distinguish individual LRA
The CAT-5 port only served to aid interconnectivity to a single artificial fingertip	Should additional fingertips be added to the system, the port would become useless	Remove CAT-5 port from design if supplementary fingertips are added
Display was distracting	User unfocused	Remove display from prototype

Table 3-3. Prototype v1.0 summary of observations and recommendations following calibration.

surface. Of course, after maximizing sensor sensitivity and several attempts to increasing the manual force upon the fingertip to achieve greater feedback, the thin layer of rubber compound on the fingertip eventually degraded and ended up peeling off, leaving some of the embedded sensors exposed. The Pro Micro suffered catastrophic damage during the calibration of the v1.0 prototype, as the mini-USB broke away from the board due to excessive strain upon the cable by leaning the glove on the table.

Prototype v1.0 was a large step forward in the overall progress of a workable tactile feedback system leading to the experimentation phase. Observations and recommendations for improvement were derived from the difficulties encountered while calibrating, which are summarized in Table 3-3.

3.2.6 Prototype v2.0

The recommendations in Table 3-3 were consequently used as a basis for improvement in the subsequent prototype version 2.0. Using a cyclic design for rapid prototyping is beneficial to increase system performance in a shortened period of time. As the ethics application for this thesis had been approved weeks ago, it was important to quickly achieve a prototype that could be employed for experimentation and hypothesis validation. Therefore, recommendations from v1.0 were adopted for use in prototype v2.0 and a wiring schematic was drafted for this version, as shown in Figure 3-19.

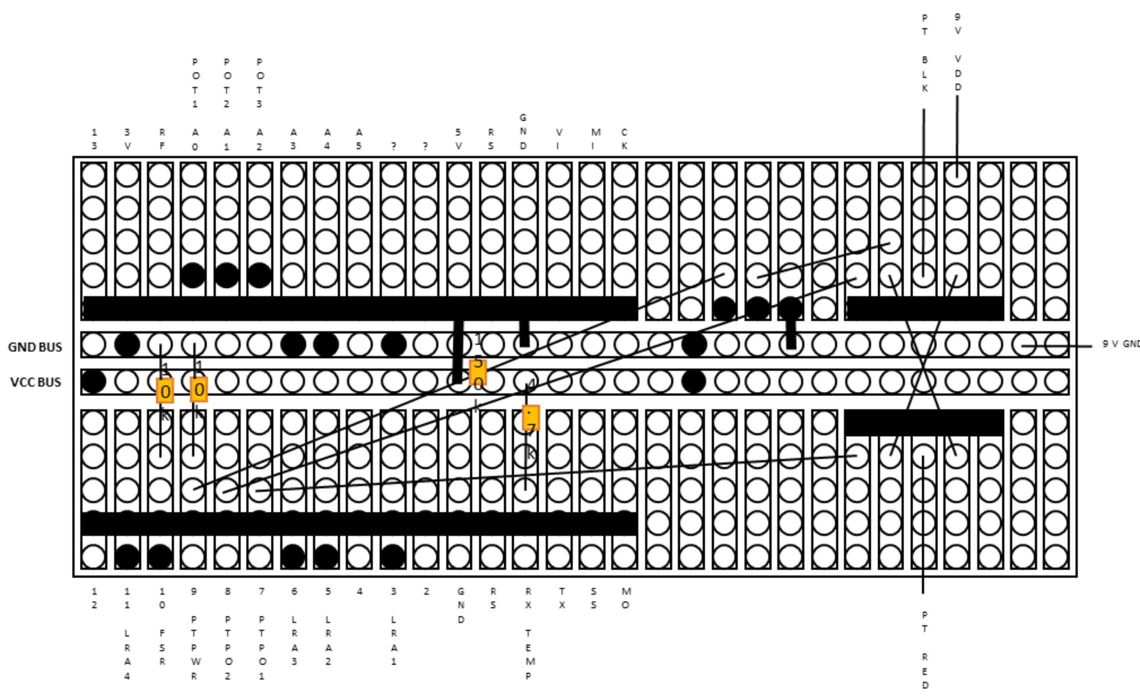


Figure 3-19. Bottom view of the Prototype v2.0 circuit board, indicating wiring connections between the Genuino Microcontroller (left), the MOSFET (centre), and the DPDT relay (right). Resistors in yellow and soldering points shown with a black dot/square, thin lines represent wires and/or resistors as indicated.

With enhancements being formalized during the creation of version 2.0, two additional fingertips were created with a fewer number of sensors in each finger due to the limited number of available analogue ports on the new microcontroller. An artificial thumb embedded with a single thin potentiometer sensor, an artificial middle finger also with a single thin potentiometer, and an artificial index finger was created containing a thin potentiometer, a temperature sensor, and an FSR. Thus the index fingertip had the most dense sensor concentration, while the middle and the thumb merely had a singular thin potentiometer. Three fingers was deemed sufficient to encompass the primary grasping tasks associated with exploratory tactile sensing, such as holding, shifting, and lifting. Note that the use of natural tactile bio-receptors was only restricted from a user's natural fingertips in order to force the use of tactile feedback received from the artificial fingertips. Other bio-receptors, such as those present in joints and muscles which provide positional feedback, as well as vibrational sensations at the junction of the wooden sticks and the natural finger backing, were allowed to be employed similarly to how an amputee would use these tactile, proprioceptive clues to complement active sensing.

Figure 3-20. Artificial fingertip.

To counteract the numbing of the user's natural mechanoreceptors from excessive LRA vibrations, modifications of the mapping from thin potentiometer sensor input to LRA vibrational pattern was necessary. In the initial prototype implementation, LRA vibrational magnitude would incrementally increase according to the position

```
Setup Microcontroller
Loop
    Read Sensor Data
    Map Sensor Data to Actuator Power Levels
    Write Mapped Data to Actuators
    Write Data to Serial Output file
Repeat Loop
```

Figure 3-21. Prototype v2.0 software sequencing.

of the force along the linear thin potentiometer strip, thereby causing a near continuously vibration from the LRA when an object was being grasped by the artificial fingertips. Certain portions of the software were modified to reflect the absence of a display unit in prototype v2.0 as well as to allow the captured data to be exportable during experimentation (Figure 3-21). The software was consequently altered such that the LRA would only vibrate when there was a *force gradient* upon the thin potentiometer sensor. In this way, the actuator would behave similarly to that of a fast-acting, mechanoreceptor nerve impulse pattern with which a human was naturally endowed. This was a small breakthrough in the behaviour of the actuators, providing a more intuitive vibrational feedback pattern and eliminating the saturation of natural mechanoreceptors due to excessive LRA use. This modification was favourably received by the glove's users, and eventually it was decided to enhance the settings one step further by only actuating the LRA upon a decrease in force (releasing the force upon an object) which further simplified the feedback to the user.

Relieving the cable strain upon the mini-USB port could only be achieved through repositioning of the microcontroller itself on the back of the glove, such that the port was oriented in a direction less susceptible to being depressed by a glove leaned against a table surface. However, repositioning of the microcontroller proved difficult given the small mountable surface area on the back of the glove and since the cable was already oriented in a suitable direction so as not to interfere with a user's grasping of an object. So it was decided that some risk would have to be accepted by keeping the microcontroller in its original position upon the circuit board, and instead caution users to be particularly careful not to rest the glove upon the table in a natural resting position, which could ultimately result in the irrecoverable damage to the only prototype available.

Prototype v2.0 of the Tactile Feedback Glove implemented the recommendations from the previous prototype version to increase the minimum threshold sensitivity for the thin potentiometer sensors. This was achieved by the use of several metal shafts of 1mm diameter inserted between the surfaces of the thin potentiometer sensor and running through the rubber compound to the surface of the fingertip. Since the density of the metal was greater than that of the rubber compound, the mechanical force exerted upon the artificial fingertip's surface was directly transferred to the sensor via

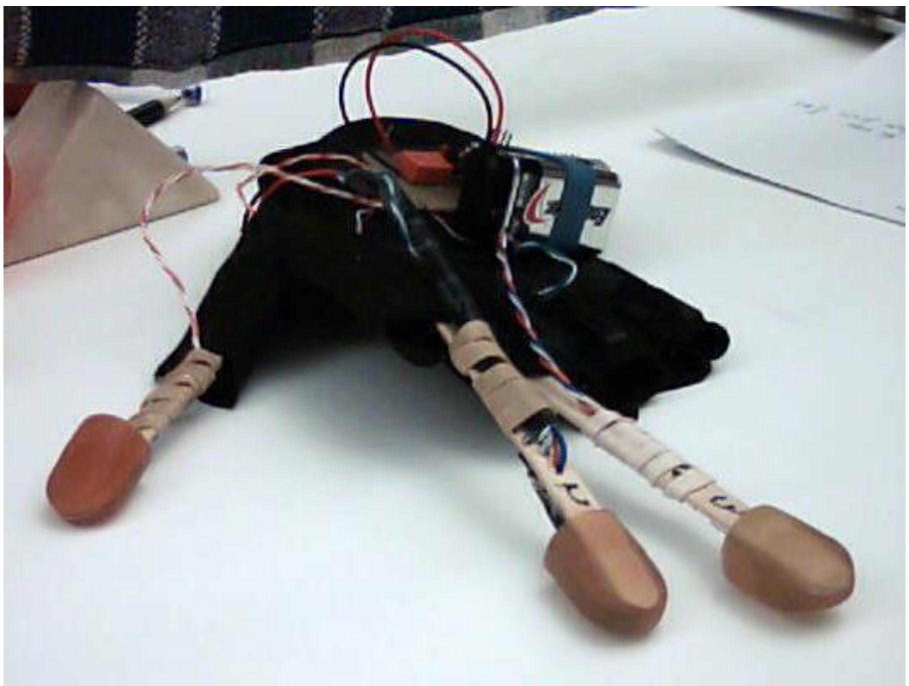


Figure 3-22. Prototype v2.0.

the metal shaft, and thereby less distorted by the semi-solid rubber. This simple solution was implemented upon the thumb and middle fingers to achieve enhancement to the thin potentiometer sensor sensitivity range.

CHAPTER 4 – EXPERIMENTATION WITH THE TACTILE FEEDBACK MODULE

As ethics approval had previously been received and the tactile feedback glove prototype v2.0 was ready for use, recruitment of subjects for participation in experiments began. Along with co-researcher Miriam Goubran, experimentation methodology was discussed, equipment was sourced, and a subject experiment schedule drafted. This section will begin by reviewing the experimental objectives and the design of the experiment sequence as well as the creation of the data collection form. It will then detail the equipment, methodology, and rationale behind key experimental setup decisions. Lastly, a brief auto critique of the overall experimental process and procedures employed will be provided.

4.1 Experimental Objectives & Sequencing

Experimental objectives were derived following a review of research questions, research objectives, and the prototype objectives. Clearly this initial series of experiments would need to focus upon the foundational aspects of this broad research area, and particular care was taken to choose experimental objectives that were both tangible and realistic. Since integration with a remotely controlled robotic finger(s) and a virtual reality environment had not yet been integrated with the tactile feedback glove, the experiment would encompass a user's tactual experience while using three artificially created fingers.

At a first glance, all of the three research questions could be partially addressed with this initial experiment. Given the configuration of the tactile feedback glove, a response to the first question (Q1) would be possible: *"Can the tactile fingertip sensations of temperature, pressure, low & high vibrations and texture be adequately remapped to another part of the hand?"* As the vibration sensor had been excluded from the fingertip due to its inability to yield meaningful results, users would have to rely upon vibrational patterns retrieved from the wooden stick attached to each of their natural fingers. Limitations on the available types of fingers (robotic & bionic) would constrain research question Q2: "*Can a human equipped with a remapped tactile feedback module accurately identify changes in temperature, pressure, low & high vibrations as well as texture from sensors located on: a prosthetic finger, a remotely controlled robotic finger, and/or a bionic supplementary finger?"* However, a partial response would be possible for Q2 in so much as the prosthetic/artificial finger would be tested. And a qualitative response to a portion of the third research question would also be possible (Q3): *"What efficacy does a tactile feedback module have in enhancing performance when using a prosthetic, a remotely controlled robotic hand, and/or an assistive bionic finger whilst conducting dexterous manipulation operations?"* Thus, with greater emphasis upon the artificially developed prosthetic finger and the actual feedback received by the users, this experiment could potentially yield greater insight into each of the three initially posed research questions.

The experiment would need to address the entire span of research objectives for it to be beneficial. Further, the experiment should also be capable of determining whether at least one of the prototype objectives had been accomplished. As the prototype objectives (PO) had been previously mapped to each of the research objectives in section 3.1, fulfillment of a PO meant that the complimentary research objectives would concurrently be addressed. After review, it was determined that given the available materials for the experiment, PO1 was reasonably expected to be accomplished: "Remap lost sensory abilities to another part of the body." Therefore, key research objectives O1, O2a, & O3 could also be covered with a properly executed experimental methodology. With the research main hypothesis in mind: *Tactile feedback rendering significantly increases a subject's ability to perform dexterous manipulation tasks*, three experimental objectives were henceforth conceived.

Experimental Objective #1 (EO1) – Ascertain whether the tactile sensory feedback system enhances manual dexterity and mystery object identification. This rather broad objective would address a wide spectrum of system related questions including, but not limited to: Are the sensors performing as expected and are they the right type/quantity of sensors for the desired outcome? Does feedback yield improved performance for dexterous manipulation? What tactile sensory clues led to object identification? Was the artificial fingertip control mechanism suitable to the task and easily controlled? Did the control mechanism for the artificial fingers impact the interpretation of tactile feedback information?

Experimental Objective #2 (EO2) – Identify whether actuators are identifiable and whether they convey sufficient information to the user given the prototype v2.0 configuration. Are the actuators correctly placed? Does the provided feedback allow the user to readily identify the stimuli? Is the actuation in a format that is appropriate for the user? Can the user detect when the actuator intensity varies? Is the time delay between sensor detection and user interpretation minimized? Are the actuators of the right type and quantity?

Experimental Objective #3 (EO3) – Capture recommendations for enhancement to the tactile feedback system. Feedback on the tactile feedback system is important. Particularly when a researcher is seeking to improve upon an existing prototype.

A successful experiment has several critical enabling factors which ultimately affect its results. Some of the experiment enabling factors that were brainstormed were: each subject has read and signed the ethics consent form, each subject has full range of natural sensory abilities in order to detect actuators and control the artificial fingers, the prototype is tested prior to each subject and is correctly functioning as intended, a training period is allotted for the user to become familiar with the prototype, each subject's other senses (vision, hearing) are restricted during experimentation, a debrief is conducted immediately following the experiments in order to capture subject feedback. This led us to create a sequence of events as well as a data collection form which can be found in *Appendix C*.

Experimental Sequencing

- Initial brief & consent
- Sensory test
- Participant preparation
- Training
- Experiments
- Debrief & Data Authentication

Figure 4-1. Experimental Sequencing.

Following the initial introduction and signing of the consent form, subjects would undergo a brief sensory test upon the same hand that would be wearing the glove. The intention of the sensory test was to confirm that the subject was able to perceive the required mechanical and thermal feedback on the parts of their hand which would be stimulated with the feedback module's actuators. Therefore, the subject was asked to close their eyes as a researcher gently depressed each area of the hand with the end of a pencil and the subject was asked to indicate whether they could feel the pencil when placed upon their hand. Once completed, a Peltier tile was then shown to the subject and the functioning of the tile was subsequently explained. Then the subject was asked to hold the Peltier tile against the lower palmar region of the thumb as the tile was connected to a battery. Once the subject was able to identify both hot and cold (when the polarity was reversed) sensations, the subject's natural senses were deemed suitable to continue with the remainder of the experiment. The subject was then asked to don the prototype glove v2.0 as one of the researchers attached the artificial fingers to the subject's hand.

4.2 Equipment & Setup

Prior to the experiment the room was setup with a large desk and facing chair for the subject, with additional chairs on either side of the subject for the researchers. The large desk was covered with a vibration-reducing tarp in order to prevent sounds from objects being dropped on the table thereby providing clues as to the object's identity. Approximately half of a metre in front of the subject upon the table was the flat face of a two-legged partition bulletin board which had a thin layer of fabric covering the opening at the base of the partition. This provided an opaque screen which shielded the subject's view of the prototype glove when the subject's hand was slid underneath the fabric and placed on the table at the other side of the partition (see Figure 4-2). This would permit researchers the ability to view and manipulate objects and the prototype glove within the tabletop experimentation area without the

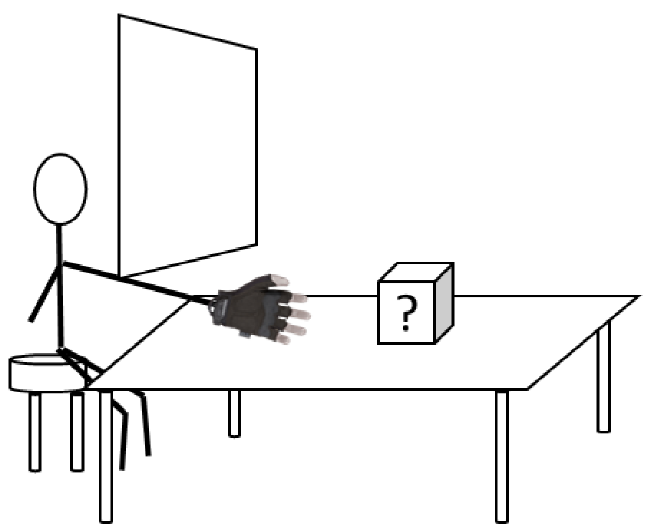


Figure 4-2. Experimental Setup. A seated subject (left) wearing the tactile feedback glove behind an opaque screen, attempting to identify the mystery object (right) on the table using tactile feedback.

subject seeing, as the experimentation area was concealed by the partition divider and the fabric attached to the bottom of the divider. A laptop computer was placed at the corner of the partition divider on the table and was connected to the glove via USB cable as well as connected to a web camera that would record movements within the experimentation area. The USB cable permitted data capture from the prototype glove's sensors and actuators while concurrently providing power to the microcontroller.

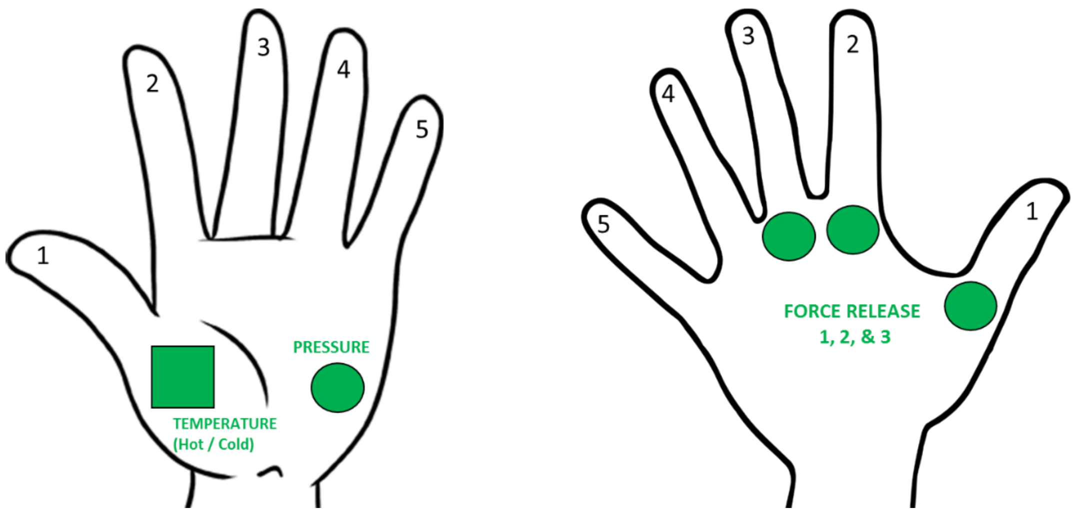


Figure 4-3. Left hand quick reference sheet, placed directly in front of subject to facilitate the oral description of sensations felt while using the glove during experimentation.

Directly in front of the subject, pinned to the partition atop the table, was a left hand quick reference guide that would be employed by the subject to orally identify the sensations felt whilst using the prototype glove (Figure 4-3). Fingers were numbered using a scheme similar to that used by pianists, the LRA actuators are indicated by a green circle, and the thermoelectric/Peltier tile is indicated with the green square. The temperature sensor in the fingertip functioned well, but the Peltier tile was manually actuated during the experiment for lack of objects with thermal properties. A total of six sensations were artificially actuated by the glove at locations indicated in figure 37 when using the artificial fingertips: four vibratory (LRA) and two thermal (Peltier).

A variety of objects were selected to be used during the course of experimentation, some with different and some with identical properties. A grand total of 21 objects made of many types of material (wood, plastic, metal, fabric, etc.) that varied in size, weight, and shape were employed during training, practice, and actual experimentation. The objects were chosen due to their small size and fine, tactual attributes which would provide tactile clues to subjects during active touch exploration. The objective for the subject was to identify the object using strictly tactile feedback using the glove. Photos of objects are displayed in Figure 4-4.

Figure 4-4. Objects used for tactile experimentation numbered 1-22 (pen used for scale): 1. plastic toy alligator, 2. plastic warrior figurine, 3. wooden die, 4. plastic puck, 5. plastic golf ball, 6. plastic spider, 7. plastic police badge, 8. metal tweezers, 9. plastic tiara, 10. soft plastic squeezable frog, 11. ceramic chest, 12. wooden triangular block, 13. wooden rectangular block, 14. wooden semi-hemispherical block, 15. measuring tape, 16. foam brain, 17. foam ball, 18. rubber bouncy ball, 19. plastic squeezable ball, 20. latex-wrapped stress putty, 21. bear plush toy, 22. cow plush toy.

4.3 Experimental Procedures

Following the tactile sensory tests described at the end of section 4.1, subjects were asked to put on the glove so that the artificial fingers could be secured to their natural fingers. Electrical tape was carefully and securely wrapped around the length of each subject's gloved fingers. This was done for two purposes: to secure the wooden craft sticks to the back of each natural finger in order to control the artificial fingertips for active tactile manipulation, and to mask the natural mechanoreceptors within each subject's fingers with layers of tape. Once the taping was complete and the artificial fingers met using a natural grasping motion of the three artificial fingertips, the subject was given an opportunity to use the glove without sensory feedback activated. Subjects sat in a chair with visual and auditory senses unobstructed and the 22 objects were placed upon the table for them to manipulate and practice manual dexterity with their newfound prosthetic fingers. Subjects were encouraged to use only the glove's artificial fingers while touching objects and were cautioned against use of their natural fingers.

An initial five minute familiarisation period comprised of moving the objects, grasping them, squeezing them, and finally placing each of them into a cardboard box. Next, the glove was powered on, a function test was performed to ensure each actuator would relay tactile sensations from the artificial fingertips, and the five minute training period was repeated again but with the powered glove. Each of the two sets of training periods was conducted sequentially and the subject was allowed to view the objects in front of them while they manipulated objects with the artificial fingers on the glove.

Once the subject had had an opportunity to use the powered glove freely to manipulate objects, the directed training commenced. During the first directed training exercise entitled 'passive touch,' the subject placed the gloved hand palmar region downwards upon the table in the concealed experimentation area. Force release, pressure, and temperature sensors were randomly stimulated by one researcher while the subject told the recording researcher specifically what was felt using quick reference indications such as, “Force 1” or “Heat.”

The training then proceeded to conduct the first active touch, exploration activity. A mystery object chosen from one of the 22 objects was concealed within the experimentation area but within reach of the subject’s gloved hand. The subject was then asked to use the artificial fingers to explore the mystery object and while exploring, describe each sensation or tactile clue that would assist in the potential identification of the hidden object. The recording researcher would then write the subject’s description upon the data collection form and prompt the subject to explain the sensations felt while exploring the object’s properties (Figure 4-5). No time limit was accorded to any portion of the touch experiments since subjects were using an unfamiliar device. When the subject believed to have completed an extensive search and accumulated sufficient clues to determine which of the 22 objects was behind the fabric curtain divider, they were asked to orally identify the object. The subject was then shown which object was hidden from them. It is important to note that up to this point in the training, subjects were permitted to employ all of their natural senses, including auditory, to assist in the identification of the mystery object.

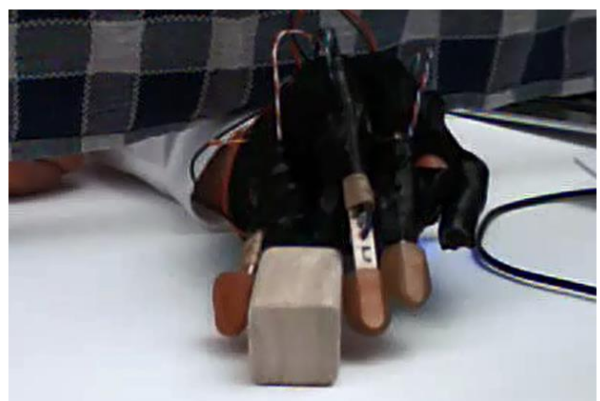


Figure 4-5. Subject exploring an object, with fingers taped, behind fabric screen.

The final training activities, items 2.3 and 2.4 on the participant data form in *Appendix C*, were a repeat of passive and active touch sequences previously described in the preceding paragraphs with one subtle difference. From this point onwards, hearing protection would be worn to mask any audible vibratory clues that may have been detected from moving or dropping the object upon the table surface. Thus, all natural senses were constrained for the remainder of the experiment (sight, auditory, tactile on natural fingers) so that the subject would make maximum use of the artificial fingertips in an attempt to ascertain object identity through the tactile feedback received from actuators in the glove. At last the user training with the glove came to an end and it was time to begin the true experimental portion of the research.

Four experiments were conducted with the subject. The first comprised of six randomly ordered sensations using passive touch, in which a researcher would stimulate a sensor and the subject would be expected to indicate which of the six actuators were consequently being activated. The last three experiments were active touch activities with mystery objects, where the subject would attempt to ascertain the object's identity through tactile clues collected during manipulation of the object in the concealed experimentation area. The first two of three active touch experiments employed mystery objects that were common for every subject, namely the plastic toy alligator (item 1 in Figure 4-4) and the wooden triangular block (item 12 in Figure 4-4). For the remaining and final active touch experiment, subjects were provided a mystery object which was randomly selected from the 22 different objects by one of the researchers.

At the conclusion of the experiments, the subject was debriefed while the tape and glove were removed. The debrief consisted of a series of questions regarding the identification process, how confident the user was regarding object identification, and asked for feedback regarding the glove. The mystery objects were then revealed to the subject and each subject was asked to keep the experimental results confidential, so that any of their friends who may be participants of the experiment remain unbiased. The subject then verified all of the data recorded on the five page, data collection form to ensure correctness and initialled the document as proof of validation. Subjects were thanked for participation in the study and reminded that if they felt they were treated unfairly or would like to lodge a complaint regarding the experiment or researchers, they could contact the university ethics board using the contact information previously provided.

CHAPTER 5 – RESULTS & ANALYSIS

This chapter will highlight the outcomes of experimentation and provide a thorough analysis of the entire experimental process.

5.1 Results

Five subjects participated in the tactile experiments (two male, three female) aged 19 to 50 years old. All subjects were right handed, and they all wore the tactile feedback glove on their less dominant hand. No medical conditions were indicated by subjects nor observed during tactile testing that would distort the results of experimentation. The subjects were recruited via two means of advertising: During a biomedical engineering seminar presentation delivered on tactile feedback, and word of mouth to a local church group from co-researcher Goubran. The entire experiment lasted approximately one hour per subject, with training and preparation taking the majority of the hour. Actual experimentation time averaged 15 minutes and was the last portion of the experimental procedure.

Two types of experiments were conducted: Passive touch and Active touch. In the passive touch portion, subjects wearing the glove would place their hand palmar region downwards upon the table within the concealed experimentation area. A researcher would then individually stimulate each of the sensors on the tactile feedback glove in random order and the subject would be asked to indicate which corresponding actuator was being stimulated. The tactile indication options available to subjects were displayed on the left hand reference card (figure 37) and were as follows: F1, F2, F3, Pressure, Hot, or Cold. Results of the Passive Touch experiment are shown in Table 5. Both of the incorrect responses to the Passive Touch experiment were a result of researcher error. As the sensor corresponding to F2 was

Passive Touch	*Subject 1*	*Subject 2*	*Subject 3*	*Subject 4*	*Subject 5*
sensation 1	✓	✓	✓	✓	✓
sensation 2	✓	✓	✓	✓	✓
sensation 3	✓	✓	✓	✓	✓
sensation 4	✓	✗	✓	✓	✓
sensation 5	✗	✓	✓	✓	✓
sensation 6	✓	✓	✓	✓	✓

Table 5-1. Results of the Passive Touch experiment.

buried deep within the fingertip of the artificial index finger, it was difficult to simulate the thin potentiometer sensor by pressing the artificial fingertip. It was discovered after the first two subjects that by pinching the artificial tip at both sides and simultaneously applying direct force to either side, the F2 sensor could be triggered independently of the two other sensors in the same fingertip. From this point onwards, the sensor was actuated as planned and the appropriate feedback was identified by each proceeding subject. Overall success rate was observed to be 93.3% despite the researcher's inability to operate the F2 sensor during experiments with the initial two subjects.

The first Active Touch experiment for each of the subjects was exploring of a mystery object within the concealed experimentation area. Hearing protection was also worn to mask any possible identifiable sounds emanating from the experimentation area should objects be dropped upon the table. The object was placed within grasp of the tactile gloved hand hidden by the partition divider and provided with unlimited time in order to identify the mystery object through manipulation of the object with their artificial fingers. Mystery object #1 was the plastic alligator (object 1 of figure 38). Only two of the five subjects were able to correctly identify mystery object #1 (table 6a).

Active Touch	*Subject 1*	*Subject 2*	*Subject 3*	*Subject 4*	*Subject 5*
mystery object #1	✓	✗	✗	✗	✓

Table 5-2. Results of Active Touch mystery object #1 experiment.

The three subjects that incorrectly identified the first mystery object stated that the hidden object was the warrior figurine (object 2 of figure 38) or the plastic spider (object 6 of figure 38) based upon the indicators that the object was relatively small and light. Subjects reported that the object was not soft nor 'squishy,' not round, not flat, instead the object was plastic, was rough and caused multiple actuators to activate, most notably F2 and F3. Overall object identification success rate was 40% for mystery object #1.

The second mystery object common to all subjects was the wooden triangular prism block (object 12 of figure 38). Two of the five subjects were able to correctly identify the second mystery object, as shown in table 6b. Subject 1 was unwilling to guess what object was as insufficient tactile

Active Touch	*Subject 1*	*Subject 2*	*Subject 3*	*Subject 4*	*Subject 5*
mystery object #2	✗	✗	✓	✗	✓

Table 5-3. Results of Active Touch mystery object #2 experiment.

clues could be collected while manipulating the object using the artificial fingertips. Subjects 2 and 4 identified the mystery object to be the wooden semi-circle / half-hemisphere block (object 14 of figure 38). Attributes that led to object identification collected from the subjects included: the object was hard when squeezing it, the object was flat not round on its bottom as it slid across the table surface easily, and the shape of the object was either circular or pointed. Subjects also said that all force-release sensors were progressively more identifiable (F1, F2, and F3) as the object was grasped and consequently released. Overall object identification success rate was 40% for mystery object #2.

Mystery object #3 was a different object for each subject. To add variety and randomness to the experimentation, one of the researchers would randomly select an object prior to the final active touch experiment. Subjects were not told whether objects were common to other subjects, and all remaining

Active Touch	*Subject 1*	*Subject 2*	*Subject 3*	*Subject 4*	*Subject 5*
mystery object #3	Teddy bear	Tiara	Brain	Frog	Teddy bear
identified object	Cow	Tiara	Brain	Frog	Teddy bear
	✗	✓	✓	✓	✓

Table 5-4. Results of Active Touch mystery object #3 experiment.

objects were hidden during every portion of the active touch experiments. Overall, the subjects were able to correctly identify the randomly selected, mystery object with a success rate of 80%. The majority of the subjects used a process of elimination/categorization based upon the identifiable attributes of the tactile sensory clues to determine the identity of the mystery object. For example, “does not roll, therefore not a ball.” Or conversely, “squishy, therefore a plush toy.” Another common tactual indicator was size of the object, derived from the vibrational clues received from the wooden sticks attached to the three artificial fingers when coming into mechanical contact with each mystery object. Based upon the displacement of the fingertips when contacting the object and applying strain to the fingers, overall size could be ascertained. Subjects also reported being capable of perceiving which of the artificial fingers were grasping and letting go of objects based upon the force release actuators.

Subject performance was cross calculated based upon each subject's individual tactile results while employing the feedback glove. Response success was scored according to the overall number of

	Passive	*Active 1*	*Active 2*	*Active 3*	
Subject 1	5	1	0	0	66.7%
Subject 2	5	0	0	1	66.7%
Subject 3	6	0	1	1	88.9%
Subject 4	6	0	0	1	77.8%
Subject 5	6	1	1	1	100.0%

Table 5-5. Subject tactile performance.

experimental questions. Otherwise stated, the passive experiment had a total of 6 potentially successful responses while each of the active experiments were either successful or not, each active touch experiment was awarded a single point if successful. Subject performance varied between 66.7% and 100% (mean 80%, median 77.8%) given the total of 9 available points.

5.2 Analysis

5.2.1 Passive Tactile Experiments

Results of the passive testing revealed that subjects were able to correctly identify individual stimulation of actuators on the tactile feedback glove successfully when correctly activated by the researchers. Subjects were therefore able to isolate the individual vibrating actuator in close proximity to other actuators, placed upon the skin at the base of each finger on the back of the hand. This indicates that actuating the back of the hand is a viable option for tactile feedback as the subjects were capable of discriminating between the three force-release feedback actuators (F1, F2, & F3). Subjects instinctively linked the passive stimulation type to the feedback received while using the glove in all cases, with the exception of when the researcher was unable to stimulate the desired sensor (see the results section for a detailed explanation of the researcher error). Therefore, part of experimental objective #2 was proven to be correct, in that subjects were capable of distinguishing between specific, 1:1 mapped feedback received from each individual actuator.

The passive feedback each subject received was conducted in idealistic laboratory conditions. Sensors were stimulated directly during a timeframe when the subject's perception was isolated and was focused upon identifying a singular tactile actuator on the gloved hand. Passive tactile sensing in the natural world can be distorted or obscured when not expecting to receive such a stimuli. Thus, the positive data received from this portion of the experiment should be tempered with the strict experimental conditions which are not present when a tactile feedback system is used in the real world.

5.2.2 Active Tactile Experiments

Several key findings were made during the course of the active tactile experiments. The artificial index finger contained a thin potentiometer sensor which did not functioning like the same sensor within the other two fingers. As the index finger thin potentiometer was buried deep below the fingertip surface with an FSR and temperature sensor in front of it, sensitivity was greatly reduced. Even on maximum sensitivity settings the sensor was occluded from functioning and there was no way to add a metal shaft due to the two sensors obstructing it. Therefore a recommendation for future tactile prototypes would be to use multi-functional sensors with minimal volume, placing them as close to the fingertip surface as possible.

Sensitive area of all artificial fingertips were too small. The metal shaft was the only part of the fingertip that would actuate embedded sensor, therefore limiting feedback to a minute area of the fingertip. This caused the subject to rely on other clues to determine each mystery object's identity: vibrational feedback from the prosthetic support sticks taped to the subject's fingers, and the relative weight of the object using arm muscles and finger muscles. Due to the robustness and fidelity of the tactile sensors, one subject's comment was very appropriate: "It felt like using chopsticks at the ends of my fingers."

The importance of properly aligning the artificial fingertips on the subject's fingers could not be overstated. Due to the small area on each fingertip that had force feedback, it was crucial that the force feedback areas were appropriately oriented towards a central point of grasping. During an experiment with one particular subject, it was evident that the actuators were not being activated due to the inability to depress the metal shaft embedded in the fingertip using the subject's preferred grasping points on each finger. Special care must be taken in order to position the artificial fingertips to ensure the sensitive areas are aligned.

Having a secure connection between natural and artificial finger support was of great importance. Maximal grasping force for each artificial finger relied upon a tight taping job of the artificial and natural finger. The looser the tape tension, the less grasping power and stability that the subject would have. It was very important to the success of the experiments that the taping job was secure enough to permit adequate grasp force, yet loose enough to allow circulation in the natural fingers.

5.2.3 Experimental Objective Analysis

This section will compare results with the initial experimental objectives and explain whether the outcomes were as expected. Recommendations are provided in cases where improvements could be made.

Experimental Objective #1 (EO1) – *Ascertain whether the tactile sensory feedback system enhances manual dexterity and mystery object identification.* The addition of tactile sensory feedback with the prototype v2.0 glove was a marginal improvement over the absence of tactile feedback. Fine features of the mystery objects remained elusive to subjects, with detailed tactual rendering not achievable with the few artificial sensors embedded within the man-made fingertips. Increasing the number of sensors would be of benefit, but would have to be countered with smaller sensors due to the restrictive volume constraints of an artificial fingertip as well as the number of actuators required to relay the voluminous tactual information. The most prominent clues that subjects used to determine the identity of the mystery objects were mostly unrelated to the tactile sensory feedback provided by the prototype glove. Though the feedback provided from the glove was felt by users, they had a difficult time interpreting the tactile feedback. The control mechanism for the artificial fingers was acceptable and instinctive; similar to using one's natural fingers. Yet, due to the flexibility of the wooden craft fingers, it was extremely difficult to apply sufficient force with the artificial fingers to cause the pressure

Figure 5-1. Co-researcher Miriam Goubran using the tactile feedback system in the Bio-inspired laboratory at the University of Ottawa, May 2017. Photo courtesy of the Senate of Canada.

FSR to activate in the index finger. Perhaps a more solid spine for the finger would perform better.

Experimental Objective #2 (EO2) – *Identify whether actuators are identifiable and whether they convey sufficient information to the user given the prototype v2.0 configuration.* Though the actuators on the tactile feedback glove are easily identifiable when stimulated in isolation, the chosen actuators fail to convey sufficient tactual information so as to be employed in dexterous manipulation activities. The addition of a greater number of sensors coupled with a more robust actuation schema are required to achieve comparable performance levels as observed with a human being's natural tactile abilities. The near real-time prototype v2.0 did however achieve excellent results from a latency perspective, allowing for seamless conveyance of tactile information from artificial fingertip to the dermis of the user's hand.

Experimental Objective #3 (EO3) – *Capture recommendations for enhancement to the tactile feedback system.* The principle recommendations captured during the course of the experiment to be incorporated for improvements to the prototype v2.0 glove were: increase the number of sensors and actuators, reduce overall size by using a single circuit board with modular interface to sensors, and enhance the control mechanism for the artificial fingertips to permit the user greater stability and increased force. Though the prototype v2.0 was a successful step in the right direction towards a tactile feedback system that permits dexterous manipulation, more work is required in order to create a more intuitive and robust system comparable to one's innate tactile abilities.

CHAPTER 6 – CONCLUSIONS

When tactile sensory sensitivity was lost in subjects' natural fingertips, compensatory natural sensors took precedence to the use of the artificial feedback. The primary indicators that subjects employed to determine the identity of mystery objects were object hardness, shape, friction, weight, and size. These traits were derived from a combination of relative finger positioning feedback when fingers came into contact with the object, lifting the object, as well as through manipulation; by moving the object across the table surface. Despite providing subjects with an artificial means of tactile feedback, they preferred to rely upon their own natural mechanoreceptors embedded in muscles and joints through lifting, grasping, and sliding the object on the table than to use the foreign and unfamiliar prototype v2.0 feedback mechanisms. Thus the tendency to make use of the more familiar, innate tactile feedback dominated the less familiar, artificial means of object identification. With greater artificial sensor density in the artificial fingertip, enhanced feedback fidelity, and more training on the system, the results would likely have shown a preference for the artificial tactile feedback system.

Several subject indicated that the hearing protection provided did not completely mask the auditory clues when an object came into contact with the table. Similarly, the radio that was also turned on as background noise did not adequately provide a noise threshold sufficiently great to hide the sound caused when the object was dropped upon the table. Thus, the results of the active touch experimentation may be easily called into question and greater care would need to be made during future experimentation so as to completely isolate the tactile senses, thereby avoiding the possibility of multi-modal sensory proprioception. One subject fittingly compared the use of the prototype's artificial fingers by stating, "It felt like using chopsticks at the ends of my fingers." In fact, the same subject thereafter expressed how fortunate it was to have one's natural fingers as the use of the artificial fingers must be similar to how prosthetic devices feel when used by amputees. Another comment was that the proximity of the force release actuators made it difficult to independently distinguish each actuator's feedback during the active touch experiments. Otherwise stated, confusion between actuators existed during concurrently stimulated actuator feedback.

Some subjects felt that a full-fingered glove would have been better than the use of tape on bare natural fingers for both comfort and control of the artificial fingertips. In this way, a layer of fabric would be present between the wooden craft sticks and the natural fingers, thereby masking vibrational clues indirectly conveyed through the wooden shafts. It was difficult for users of the glove not to inadvertently touch mystery objects with their natural fingertips and accidently gain tactile information regarding the object through the thin layer of electrical tape. Ideally, the subjects that participated in the experimentation would have been victims of dismemberment and artificial fingers could have been created for them. In this way, the subjects may have appreciated the additional artificial feedback having started with little or no natural feedback at all.

In general, the prototype v2.0 delivered some very positive results and performed in a satisfactory manner. Latency was minimized to an acceptable level, subjects were able to perceive individual sensations from each of the actuators with a high degree of accuracy, and the glove had a suitable form-factor enabling subjects to manipulate objects in an innate way while receiving artificial tactile feedback. The novel temperature feedback mechanism using the thermoelectric tile allowed subjects to receive thermal feedback using a prosthetic device. Tactile feedback delivered during the moment that artificial fingertip released force, allowed users to detect subtle changes in object contact forces without being overwhelmed by a constantly buzzing actuating disk or LRA. The actuator's force release scheme mimics the natural mechanoreceptor and peripheral nervous system's tactile signal encoding, which likely explains its success during this study.

Regarding the prototype development, the effectiveness of the prototype could have been improved using a sequential testing cycle, with only a small number of subjects would trial the glove before initiating experiments with the main body of subjects. Enhancements could have been consequently made to the prototype and experimental procedures adapted based upon the sample population's feedback before enacting the full experimental sequence. Passive tactile experimentation that involved multiple, concurrent actuator feedback was not conducted and may be a future research option. Actuator and sensor placement studies would reveal ideal proximity, sites, and quantities for tactile feedback location and intensity. Evidently, once a more robust feedback system were to be created, experimentation with robotic fingers and in virtual reality settings would be a natural progression for system testing and validation.

Future work in this area that would build upon the results of this study would be to determine the most suitable positioning for the tactile feedback actuators on the hand. Once the ideal location for tactile feedback was determined, threshold testing could determine whether higher tactile feedback ratios (1:1 in this experiment) would be possible using varied actuator frequency, intensity, or combinations of feedback dimensionality. Enhanced dexterous manipulation using a tele-manipulated robotic hand with tactile feedback could also be explored such that humans could continue to operate in toxic environmental conditions. Although many of the more modern solutions for prosthetics involve surgery, I foresee the continued use of non-invasive prosthetic feedback solutions due to their relatively lower cost and modularity.

In closing, the real world is rich with tactile sensations and it is difficult to artificially replicate. The natural tactile receptors that we have been so graciously endowed with and have employed for years in the real world are personalized and unique to each of us. The tactile feedback system developed and presented herein will require a great deal of enhancement before it is capable of even coming close to rivalling the astounding abilities of the human hand. I continue to search a more suitable tactile system that can better fulfill the needs of amputees and those with tactile sensory disorders. Seeing is believing, but touch is reality.

REFERENCES

[1] R. Sekuler and R. Balke, *Perception*, McGraw-Hill, 1990.

[2] Collins English Dictionary Online, 2017: https://www.collinsdictionary.com/dictionary/english/touch. Last retrieved 28-06-2017.

[3] Oxford Online Dictionary, 2016: http://www.oxforddictionaries.com/definition/english/haptic. Last retrieved 28-06-2017.

[4] Online Dictionary, 2016: http://www.dictionary.com/browse/haptic. Last retrieved 28-06-2017.

[5] Petriu, E.M., McMath, W.S., Yeung, S.K. & Trif, N. (1992). Active Tactile Perception of Object Surface Geometric Profiles. *IEEE Trans. Instrum. Meas.,* Vol. 41, No. 1, pp. 87-92.

[6] Fulkerson, M. (2014). The first sense: A philosophical study of human touch. MIT Press.

[7] Jütte, R. (2008). Haptic perception: an historical approach. *Human Haptic Perception: Basics and Applications,* Ch. 1, pp. 3-14.

[8] Neuhäuser, J. (1878). *Aristoteles Lehre von dem sinnlichen Erkenntnisvermogen und seinen Organen.* Trans. Koschny, L., & Beare, J. (1906). *Greek theories of elementary cognition from Alcmaeon to Aristotle.* Clarendon, Oxford.

[9] Jütte, R. (2005). A history of the senses. *From Antiquity to Cyberspace,* Trans. James Lynn. Polity Press, Cambridge.

[10] Weber, E. (1905). *Tastsinn und Gemeingefühl.* Hering, E. (ed), Engelmann, Leipzig; Bueck-Rich, U. (1970) *Ernst Heinrich Weber (1795-1878) und der Anfang einer Physiologie der Hautsienne.* Juris Drück, Zurich.

[11] Jones, L.A., & Lederman, S. (2006). *Human Hand Function.* Oxford University Press Scholarship Online. DOI: 10.1093/acprof:oso/9780195173154.001.0001.

[12] Spray, D. C. (1986). Cutaneous temperature receptors. *Annual Reviews of Physiology, 48*, pp. 625–638.

[13] Lynn, B., & Perl, E. R. (1996). Afferent mechanisms of pain. In L. Kruger (Ed.), *Pain and touch* (pp. 213–241). San Diego, CA: Academic.

[14] Mechanoreceptors: http://www.pc.rhul.ac.uk/staff/J.Zanker/PS1061/L6/mechano-rec-rev.jpg. Last retrieved: 5-10-2016.

[15] Johansson, R., & Vallbo, A. (1983). *Tactile Sensory Coding in the Glabrous Skin of the Human Hand*. Technical Innovations in Neuroscience (TINS), Elsevier Biomedical Press, pp. 27-32, January 1983.

[16] Stevens, J. C. (1991). Thermal sensibility. In M. Heller and W. Schiff. (Eds.), *The psychology of touch* (pp. 61–90). Hillsdale, NJ: Erlbaum.

[17] Vallbo, A., & Hagbarth, K. (1968). *Experiments in Neurology.* Vol. 21, pp. 270-289.

[18] Vallbo, A., Hagbarth, K., Torebjork, H., & Wallin, B. (1979). *Physiology Review.* Vol. 59, pp. 919-957.

[19] Ruch, T.C., & Patton, H.D. (eds.) (1982). *Physiology and Biophysics*, 20th ed., 1242 pp. W. B. Saunders, Philadelphia.

[20] Martini, F.H., & E.F. Bartholomew. *Structure and Function of the Human Body.* Upper Saddle River, NJ: Prentice Hall, 1999.

[21] Malmivuo, J., & Plonsey, R. (1995). *Bioelectromagnetism - Principles and Applications of Bioelectric and Biomagnetic Fields*, Oxford University Press, New York, 1995.

[22] Gardner, E.P., Martin, J.M., & Jessell, T.M. (2000). The bodily senses. In E. R. Kandel, J. H. Schwartz, & T. M. Jessell (Eds.), *Principles of neural science*, 4th ed., pp. 430–450.

[23] Florence, S.L., Wall, J.T., & Kaas, J.H. (1989). Somatotopic organization of inputs from the hand to the spinal gray and cuneate nucleus of monkeys with observations on the cuneate nucleus of humans. *Journal of Comparative Neurology,* Vol. 286, pp. 48–70.

[24] Paul, R.L., Merzenich, M.M., & Goodman, H. (1972). Representation of slowly and rapidly adapting cutaneous mechanoreceptors of the hand in Brodmann's areas 3 and 1 of macaca mulatta. *Brain Research,* Vol. 36, pp. 229–249.

[25] Drachman, D. (2005). "Do we have brain to spare?" *Neurology*. Vol. 64, pp. 12.

[26] Yuste, R., & Church, G. (March 2014). "The new century of the brain." *Scientific American*. Vol. 310, 3rd ed., pp. 38–45.

[27] Angevine, J., & Cotman, C. (1981). *Principles of Neuroanatomy*. NY: Oxford University Press.

[28] Motor & Somatosensory cortex: http://images.slideplayer.com/14/4280670/slides/slide_23.jpg. Last retrieved: 14-12-2016.

[29] Vanderwerker, Earl E., Jr. (1976). A Brief Review of the History of Amputations and Prostheses. *ICIB,* Vol. 15, Ch.5, pp. 15–16.

[30] History of prosthetics: A 3000-Year-Old Toe. http://www.uh.edu/engines/epi1705.htm. *Uh.edu.,* No. 1706. Last retrieved 24-05-2017.

[31] International Standards Organization. https://www.iso.org/obp/ui/#iso:std:iso:8549:-1:ed-1:v1:en Last retrieved 28-06-2017.

[32] DARPA Prosthetic Arm. http://www.electronicspecifier.com/medical/the-most-advanced-thought-powered-prosthetic-limb. Last retrieved 28-06-2017.

[33] Bebionic3 Prosthetic Arm. http://whatsup247.info/overboard/terminator-arm-is-worlds-most-advanced-prosthetic/. Last retrieved 28-06-2017.

[34] LifeHand2. https://www.usatoday.com/story/news/nation/2014/02/05/bionic-hand-amputee-feels/5229665/. Last retrieved 28-06-2017.

[35] Dahiya, R.S., & Valle, M. (2013). *Robotic Tactile Sensing.* Springer Science + Business Media, Dordrecht: 2013.

[36] Dahiya, R.S., Metta, G., Valle, M., & Sandini, G. (2010). Tactile sensing—from humans to humanoids. *IEEE Trans. Robot.* Vol. 26, ed. 1, pp. 1–20.

[37] Loomis, J.M., & Lederman, S.J. (1986). Tactual perception. *Handbook of Perception and Human Performances*, Vol. 2. Wiley, New York.

[38] McMath, W.S., Yeung, S.K.S., & Petriu, E.M. (1989). Tactile Sensing for Space Robotics. *Proc. IMTC/89, IEEE Instrum. Meas. Technol. Conf*., pp. 128-131, Washington, DC.

[39] Okamoto, S., Nagano, H., & Yamada, Y. (2013). *Psychophysical Dimensions of Tactile Perception of Textures. IEEE Transactions on Haptics,* Vol. 6, No. 1, 2013.

[40] Yeung, S.K., Petriu, E.M., McMath, W.S., & Petriu, D.C. (1994). High Sampling Resolution Tactile Sensor for Object Recognition. *IEEE Tr. Instrum. Meas.,* Vol. 43, No. 2, pp. 277-282.

[41] Payeur, P., Pasca, C., Cretu, A.-M., & Petriu, E.M. (2005). Intelligent Haptic Sensor System for Robotic Manipulation. *IEEE Trans. Instrum. Meas.*, Vol. 54, No. 4, pp. 1583–1592.

[42] Yuji, J.I., & Sonoda, C. (2006). A PVDF Tactile Sensor for Static Contact Force and Contact Temperature. *IEEE Sensors*, Vol. 6, No. 6, pp. 738-741.

[43] Kampmann, P., & Kirchner, F. (2014). Integration of fiber-optic sensor arrays into a multi-modal tactile sensor processing system for robotic end-effectors. *Sensors,* Vol. 14, pp. 6854-6876.

[44] Hosoda, K., Tada, Y., & Asada, M. (2006). Anthropomorphic robotic soft fingertip with randomly distributed receptors. *Robot. Auton. Syst.*, Vol. 54, pp. 104–109.

[45] Ando, S., Shinoda, H., Yonenaga, A., & Terao, J. (2001). Ultrasonic six-axis deformation sensing. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, Vol. 48, No. 4, pp. 1031–1045.

[46] De Oliveira, T.E.A., Cretu, A.M., Da Fonseca, V.P., & Petriu, E.M. (2015). Touch sensing for humanoid robots. *IEEE Instrum. Meas. Mag.*, Vol. 18, No. 5, pp. 13–19.

[47] De Oliveira, T.E.A., Cretu, A.M., & Petriu, E.M. (2017). Multimodal Bio-Inspired Tactile Sensing Module. *IEEE Sensors Journal*, Vol. 17, Issue 11, pp. 3231–3243.

[48] Petriu, E.M. (2011). Biology-Inspired Multimodal Tactile Sensor System. *Proc. ROSE 2011, IEEE Int. Symp. Robotic and Sensor Environments*, pp. 54-59.

[49] Brown, J.N.A. (2015). "Once More, With Feeling": Using Haptics to Preserve Tactile Memories. *Intl. Journal of Human-Computer Interaction*, 31, pp. 65-71.

[50] Wada, C., Shoji, H., & Ifukube, T. (1999). Development and evaluation of a tactile display for a tactile vocoder. *Technology and Disability,* 11, pp. 151-159.

[51] Vishniakou, S., Lewis, B., et al. (2013). Tactile Feedback Display with Spatial and Temporal Resolutions. *Scientific Reports,* 3:2521, DOI: 10.1038/srep02521.

[52] Benali-Khoudja, M., Hafez, M., Alexandre, J.-M., & Kheddar, A. (2004). Tactile interfaces: A state-of-the art Survey. *Proc. ISR 2004 -35th Intl. Symp. Robotics*.

[53] Wide, P., Petriu, E.M., & Siegel, M. (2010). Sensing and Perception for Rehabilitation and Enhancement of Human Natural Capabilities. *Proc. ROSE 2010, IEEE Int. Workshop on Robotic and Sensor Environments*, pp. 75-80.

[54] Chouvarda, V.G., Miliou, A.N., & Hatalis M.K. (2008). Tactile Displays: Overview and recent advances. *Displays*, Science Direct, 29, pp. 185-194.

[55] Sokhanvar, S., Dargahi, J., Najarian, S., & Arbatani, S. (2013). *Tactile Sensing and Displays: Haptic Feedback for Minimally Invasive Surgery.* 1st ed., Ch. 7, pp. 131-146, John Wiley & Sons.

[56] Franco, M. L., King, C.-H., Culjat, M. O., Lewis, C. E., Bisley, J. W., Holmes, E. C., Grundfest, W. S. & Dutson, E. P. (2009), An integrated pneumatic tactile feedback actuator array for robotic surgery. Int. J. Med. Robotics Comput. Assist. Surg., 5: pp. 13–19.

[57] Paschew, G., & Richter, A. (2010). High-resolution display operated by an integrated “Smart Hydrogel” actuator array. *Proc. of SPIE*, Vol. 7642, pp. 341-348.

[58] Ninomiya, T., Okayama, Y., Matsumoto, Y., Arouette, X., Osawa, K., & Miki, N. (2009). MEMS-based hydraulic displacement amplification mechanism with completely encapsulated liquid. *Sensors and Actuators A*, Vol. 166, pp. 277-282.

[59] Petriu, E.M., & McMath, W.S. (1992). Tactile Operator Interface for Semi-autonomous Robotic Applications. *Proc. Int. Symposium on Artificial Intell. Robotics Automat. in Space, i-SAIRS'92*, pp. 77-82.

[60] Son, C., Ko, K., Lee, H.J., Na, K., Han, J., Yun, K.S., Yoon, E.S., Kim, E., & Cho, I.J. (2016). A flexible multimodal tactile display array for virtual shape and texture. *Microsyst. Technol.*, Vol. 22, pp. 2587-2594.

[61] Deng, K., & Enikov, E.T. (2010). Design and development of a pulsed electromagnetic micro-actuator for 3D virtual tactile displays. *Mechatronics*, Vol. 20, pp. 503-509.

[62] Benali-Khoudja, M., Hafez, M., & Kheddar, A. (2007). VITAL: An electromagnetic Integrated Tactile Display. *Displays*, Vol. 28, pp. 133-144.

[63] Nara, T., Takasaki, M., Maeda, T., Higuchi, T., Ando, S., & Tachi, S. (2001). Surface Acoustic Wave Tactile Display. *IEEE Comput. Graph. Appl.*, **21**(6), pp. 56-63.

[64] Runyan, N.H., & Carpi F. (2011). Seeking the ‘Holy Braille’ Display: Might Electromechanically Active Polymers be the Solution? *Expert Review of Medical* Devices, vol. 8, no. 5, pp. 529+.

[65] DEA 2: Phung, H., Nguyen, C.T., Nguyen, T.D., Lee, C., Kim, U., Lee, D., Nam, J., Moon, H., Koo, J.C., & Choi, H.R. (2015). Tactile display with rigid coupling based on soft actuator. *Meccanica*, Vol. 50, pp. 2825-2837.

[66] Di Spigna, N., Chakraborti, P., Winick, D., Yang, P., Ghosh, T., & Franzon, P. (2010). The Integration of Novel EAP-based Braille Cells for use in a Refreshable Tactile Display. *Proc. of SPIE*, Vol. 7642, pp. 0A-1 to 9.

[67] Matsunaga, T., Totsu, K., Esashi, M., & Haga, Y. (2013). Tactile display using shape memory alloy micro-coil actuator and magnetic latch mechanism. *Displays*, Vol. 34, pp. 89-94.

[68] Hussain, I., Meli, L., Pacchierotti, C., Salvietti, G., & Prattichizzo, D. (2015). Vibrotactile Haptic Feedback for Intuitive Control of Robotic Extra Fingers. *IEEE World Haptics Conference,* 2015, pp. 394-399.

[69] Choi, S., & Kuchenbecker, K. (2013). Vibrotactile Display: Perception, Technology, and Applications. *Proc. of the IEEE,* Vol. 10, No. 9, 2013, pp. 2093-2104.

[70] Kajimoto, H. (2010). Electro-tactile Display with Real-Time Impedance Feedback. *EuroHaptics 2010,* Part I, LNCS 6191, pp. 285-291.

[71] Uematsu, H., Suzuki, M., Kanno, Y., & Kajimoto, H. (2016). Tactile Vision Substitution with Tablet and Electro-Tactile Display. *EuroHaptics 2016,* Part I, LNCS 9774, pp. 503-511.

[72] Gallo, S. (2016). Wearable multimodal tactile interfaces for augmenting haptic perception. PhD Thesis, No. 6872, École Polythechnique Fédérale de Lausanne.

[73] Bark, K., Wheeler, J., Shull, P., Savall, J., & Cutkosky, M. (2010). Rotational Skin Stretch Feedback: A Wearable Haptic Display for Motion. *IEEE Trans. on Haptics,* Vol. 3, No. 3, pp. 166-176.

[74] Janko, M., Primerano, R., & Visell, Y. (2016). On Frictional Forces between the Finger and a Textured Surface during Active Touch. *IEEE Trans. on Haptics,* Vol. 9, No. 2, pp. 221-232.

[75] Kim, S-C., Israr, A., & Poupyrev, I. (2013). Tactile Rendering of 3D Features on Touch Surfaces. *UIST '13,* October 2013, St. Andrews, United Kingdom.

[76] Nasu, A., Kotani, K., Asao, T., & Nakagawa, S. (2011). Information Processing for Constructing Tactile Perception of Motion: A MEG Study. *Human Interface,* Part I, HCII 2011, LNCS 6771, pp. 478-487.

[77] The Knick Finger, created by Nick Brookins of Danger[creations].inc. https://www.thingiverse.com/thing:1340624. Last retrieved: May 2017.

[78] Body heat powered flashlight. http://www.instructables.com/id/Body-Heat-Powered-Flashlight/. Last retrieved: May 2017.

[79] DS18B20 temperature sensor code and description, by Simon Tushev, published 5 Aug 2013. https://tushev.org/articles/arduino/10/how-it-works-ds18b20-and-arduino. Last retrieved: May 2017.

[80] OneWire bus sample code for the DS18B20 temperature sensor, courtesy of Arduino.cc. http://playground.arduino.cc/Learning/OneWire. Last retrieved: May 2017.

[81] OneWire bus sample code for multiple DS18B20 sensors on one wire bus. https://www.pjrc.com/teensy/td_libs_OneWire.html. Last retrieved: May 2017.

[82] Double Pole, Double Throw Thermoelectric tile with MOSFET regulator solution. http://www.instructables.com/id/BioMONSTAAAR-HC-Control-Board/. Last retrieved: May 2017.

[83] High-Power Control: Arduino + N-channel MOSFET regulator, 5 March 2012. http://bildr.org/2012/03/rfp30n06le-arduino/. Last retrieved: May 2017.

[84] How to use a Peltier with Arduino, GarageLab, 10 Sept 2012. http://garagelab.com/profiles/blogs/how-to-use-a-peltier-with-arduino. Last retrieved: May 2017.

APPENDICES

Appendix A – Research Ethics Application

uOttawa

UNIVERSITY OF OTTAWA

APPLICATION FORM FOR ETHICS APPROVAL

Researchers applying for ethics approval are expected to have read the *Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans* (2nd ed. 2010) as it sets out the ethical guidelines for conducting research with human participants. At the end of this application your signature attests to the fact that you have read this document. When completing this application form, be sure to respond to all items.

1. RESEARCH PROJECT REGISTRATION

1.1 Project title: Tactile Feedback using Prosthetic/Robotic Fingers

1.2a Anticipated project dates Start date: 2016-08-15 Completion date: 2017-08-15

1.2b Is there a pending deadline by which ethics approval is required? ○ Yes ◉ No

Deadline date:

Please provide reasons:

1.3 **Principal investigator. [If this is a 4th year, Master's or Doctoral project, indicate your supervisor's name a contact information in Section 1.4]**

Name: Daniel J. Kucherhan

○ Professor ○ Ph.D. ○ M.D. ○ Miss ○ Ms. ○ Mrs. ◉ Mr. ○ Other

Department: SITE Faculty: Biomedical Engineering

Address: Room STE-5041, 800 King Edward, Ottawa, Ontario, Canada, K1N 6N5

Telephone no.: 613-562-5800 Ext.: 2132 Fax no.: 613-562-5664

E-mail:

1.4 Thesis/Project Supervisor

Name: Emil Petriu

(●) Professor ( ) Ph.D. ( ) M.D. ( ) Miss ( ) Ms. ( ) Mrs. ( ) Mr. ( ) Other

Department: SITE Faculty: Electrical Engineering and Computer Science

Address: Room STE-5041, 800 King Edward, Ottawa, Ontario, Canada, K1N 6N5

Telephone no.: 613-562-5800 Ext.: 2132 Fax no.: 613-562-5664

E-mail: petriu@uottawa.ca

1.5 Co-investigator

Name: Vinicius Prado da Fonseca

Role in research project: Robotic Tactile Manipulation Expert

( ) Professor ( ) Ph.D. ( ) M.D. ( ) Miss ( ) Ms. ( ) Mrs. (●) Mr. ( ) Other

Department: Electrical and Computer Engineering Faculty: Engineering

Address: Room STE-5041, 800 King Edward, Ottawa, Ontario, Canada, K1N 6N5

Telephone no.: Ext.: Fax no.:

E-mail:

Add a co-investigator

Name: Miriam Goubran

Role in research project: Health Sciences and Psychology Expert

( ) Professor ( ) Ph.D. ( ) M.D. ( ) Miss (●) Ms. ( ) Mrs. ( ) Mr. ( ) Other

Department: Health Sciences Faculty: Interdisciplinary School of Health Sciences

Address:

Telephone no.: Ext.: Fax no.:

E-mail:

Remove

Add a co-investigator

Name:

Role in research project:

◯ Professor ◯ Ph.D. ◯ M.D. ◯ Miss ◯ Ms. ◯ Mrs. ◯ Mr. ◉ Other

Department : Faculty :

Address :

Telephone no. Ext.: Fax no.:

E-mail:

Remove

Add a co-investigator

1.6 Type of research

◯ Professor's research

◯ Doctoral thesis — Please append the thesis committee's approval

◉ Master's thesis

◯ Master's major research project

Please append the thesis committee's approval. In cases where there is no committee, append a letter signed by the supervisor indicating that the supervisor has reviewed and approves the proposed research project.

◯ 4th year project

◯ Independent study project

◯ Other (Please specify):

1.7 Funding information

◯ Received ◯ Pending ◉ Not required

Name of funding agency:

U of O RE No. or Cost Centre or Funding Agency Reference No.:

Have you applied for preliminary authorization of release of funds (1b approval)? ◯ Yes ◉ No

! File No.:

2. RESEARCH PROJECT DESCRIPTION

2.1 Purpose: Describe the project and its objectives. Please include the research questions. (1 page)

The purpose of this study is to investigate how the highly sensitive tactile sensations normally felt in the human fingertip can best be remapped to a different part of the dermis on the hand. This non-invasive remapping will benefit those who wear a prosthetic or bionic finger, for those who seek to remotely operate assistive robotic fingers for dexterous manipulations, and may allow enhanced tactile feedback experience while interacting in the real world or in virtual reality environments.

RESEARCH QUESTIONS:

Q1: Can the tactile fingertip sensations of temperature, pressure, low & high vibrations and texture

be adequately remapped to another part of the hand?
Q2: Can a human equipped with a remapped tactile feedback module accurately identify changes in temperature, pressure, low & high vibrations as well as texture from: a prosthetic finger, a remotely controlled robotic finger, and/or a bionic supplementary finger?
Q3: What efficacy does a tactile feedback module have in enhancing performance when using a prosthetic, a remotely controlled robotic hand, and/or an assistive bionic finger whilst conducting dexterous manipulation operations?

OBJECTIVES:
O1. Evaluate tactile feedback techniques and locations for remapping of fingertip sensations.
O2. Design prototype to test the chosen tactile feedback solution with three use cases:
 a. Prosthetic finger;
 b. Remote robotic finger; and
 c. A bionic 'sixth' finger used for assistive gripping.
O3. Validate the value of the chosen feedback technique through experimentation with human subjects.

HYPOTHESIS:
Tactile feedback rendering increases a subjects ability to perform dexterous manipulation tasks.

2.2 Context: Situate the project in the scholarly literature and provide the rationale for the study. (1-2 pages)

Humankind's understanding of the physiology related to tactile sensing has advanced significantly since the 21st century. However, the peculiarities of vibrotactile perception and the novelty of vibrotactile technology can make it difficult for designers new to this area to create effective displays. [1] A suitable 'tactile language' has yet to be created that conveys temperature, texture and high-resolution, tactile discrimination. Though many commercial vibro and electro-tactile displays are found on the market today, no single unit is able to adequately convey the full spectrum of sensational complexities of human haptics. [2]

Humans use two distinct aspects of haptics to receive sensory inputs: Tactile (cutaneous) sensing and kinesthetic (proprioceptive) sensing. [3] When employed in combination, the two aspects are able to allow a human to perceive one's physical environment. However, when dismemberment occurs, the sensing capability of the lost appendage is equally lost.

Similarly, the performance of dexterous manipulation tasks require a high level of compliant control. Grasping and reorientation of common objects is a relatively simple task for a human, however a very complex endeavour for robots. Humans who have lost motor strength in their appendages often require assistance to manipulate, grasp and reorient objects. [4]

Combining a tactile feedback rendering unit with a compliant control device, such as a sixth finger, will enable a new generation of prosthetic and robotic assistive devices. This study will focus upon sensory feedback in combination with control mechanics to improve the level of human sensory ability and performance during dexterous manipulation tasks.

2.3 Methodology/Procedures: Describe all methods and procedures that will be used to obtain data and answer the research questions. (1-2 pages)

METHODOLOGY
This research will be conducted systematically and sequentially over the course of four distinct phases as follows:

Phase 1 – Acquisition of equipment and prototyping.
Construct a suitable glove that will serve concurrently as a tactile-sensation interface and as a mounting base for previously designed prosthetic/robotic fingers. Based upon scientific research, use suitable materials and techniques required to transfer tactile sensations both locally and remotely. A prototype will be developed by the aforementioned researchers using commercial-off-the-shelf equipment.

Phase 2 – Human testing of glove for remote tactile feedback of a robotic finger.
A human wearing the tactile feedback glove will perceive the aforementioned tactile sensations from a stimulated robotic finger. The data will be relayed using electronic means between robotic fingertip and glove. The data will subsequently drive transducers found within the glove that will allow the relay of tactile sensory information to the human subject. Variations in stimuli (temperature, vibration, pressure and texture) will be presented to the robotic finger, out of sight from the human subject, who will be asked to describe what stimuli is being tactually perceived using the glove.

Phase 3 – Human testing of glove for tactile feedback of a bio-mechanically actuated, prosthetic finger.
A human who is missing an index finger will wear a prosthetic finger that is attached to the tactile feedback glove. The prosthetic fingertip will convey sensory data to the remapped tactile feedback portion of the glove, thereby allowing the wearer to sense temperature, vibrations, pressure and texture through the prosthetic finger. Variations in stimuli (temperature, vibration, pressure and texture) will be presented to the prosthetic finger, with the human subject's remaining fingers as well as auditory and visual senses deprived. The subject will be asked to describe changes in stimuli as perceived from the remapped tactile portion of the glove. Additionally, the subject will be asked to perform exploratory tactile sensing using the prosthetic finger in an attempt to ascertain properties and ultimately the identity of several mystery objects.

Phase 4 – Human testing of glove for tactile feedback of a 'sixth' bionic finger used for assistive gripping.
A human will wear the tactile feedback glove fitted with an additional opposable thumb. This synthetic thumb will extend and contract in concert with the real thumb and fingers of the hand. The tip of the synthetic thumb will relay sensory information to another part of the hand using the tactile feedback portion of the glove. Experiments of grasping and manipulating household objects using a sixth finger, including and excluding tactile feedback, will be conducted and human subject qualitative results will be obtained.

PROCEDURES
Student volunteers for phases 2 & 4 will be recruited from within the Biology-Inspired (BioIn) laboratory of the SITE building. A volunteer human participant has already been identified for phase 3 of the study. All participants will briefed using the enclosed informed consent form, secondary use of data form and the debriefing form. Each volunteer participant will be given a unique identifier number so that personal data may be kept separately from the data captured. Personal information of participants will be collected for the purposes of this study: name, age, sex, handedness, previously diagnosed tactile sensitivity disorders, and contact information. Personal information will be stored on removable media and kept separately from research data collected.

Collected data during phases 2-4 will include: human subject perceived sensations (passive tactile feedback), object identification using a mechanically controlled prosthesis with feedback (active tactile feedback), and grasping performance with/without tactile feedback. The data will be captured electronically by the investigators based upon the verbal responses of the subjects.

2.4 Data analysis: Describe how the data will be analyzed. (1 page)

The collected data described in section 2.3 will be analyzed by comparing controlled variables of temperature, vibration, pressure, texture and object type with the human subject's verbally described, perceived tactile sensations.

Data that may be subject to secondary use of data includes: transcribed qualitative responses from subjects regarding sensations felt while wearing the glove, quantitative information regarding pressure and tactile input to the prosthetic / robotic finger, and non-attributable personal information regarding age/sex/handedness/sensory processing disorder/ASD. No data will be subject to secondary use without the future consent of the subject.

2.5 Describe the anticipated contribution of the research. (1 page)

It is anticipated that this research will contribute to the greater scientific and medical communities through the design of a more robust haptic device-human feedback interface in concert with an existing control mechanism. Applications may include, but are not limited to: Remote dexterous manipulation of robotic hands, enhanced tactile feedback for robotic assisted surgery, virtual reality, and advanced prosthetics.

2.6 References: Include author, year, title, journal, page numbers (1-2 pages)

[1] Choi, S. and Kuchenbaker, K. (2013). "Vibrotactile Display: Perceptions, Technology, and Applications," Proceedings of the IEEE, Vol. 101, No. 9, 2093-2104.
[2] Antfolk, C. Balkenius, G. Lundborg, B. Rosen, & F. Sebelius (2010). "Design and Technical Construction of a Tactile Display for Sensory Feedback in a Hand Prosthesis System," BioMedical Engineering OnLine 2010, 9:50.
[3] L. A. Jones & N. B. Sarter (2008). "Tactile Displays: Guidance for Their Design and Application," HUMAN FACTORS, Vol. 50, No. 1, February 2008, pp. 90–111.
[4] MIT-assistive fingers project http://news.mit.edu/2014/getting-grip-robotic-grasp-0718

3. RECRUITMENT OF PARTICIPANTS

3.1 Who is being recruited? Describe the specific inclusion criteria for participants to be involved in the study.

Inclusion criteria include: willingness to participate, permission to use data for scientific research and be of minimum age = 18 years. Additionally, subjects for phase 2 of the study are required to have at least one dismembered finger on either or both of their hands.

3.2 Indicate the number of participants in the study.

During Phases 2 & 4: 2 - 20 participants.

During Phase 3: 1 - 5 participants.

3.3 What is the rationale for the intended number of participants?

To provide greater power to experimental data. This study is exploratory in nature. Participants for phase 3 are likely to be more difficult to source, as they are required to be missing one or more of their natural fingers.

3.4 In some cases, the number of interested participants who meet the inclusion criteria exceeds the desired number of participants.

Will all eligible individuals who volunteer be included in the study?

( ) Yes (•) No

If no, please describe how you will make the selection (e.g., first come/first served) and how participants will be informed of this.

First come / first selected. Surplus participants will be notified that they were "...regretfully not accepted as the maximum number of participants has been reached."

3.5 In some studies, there are additional scientific criteria which require the exclusion of potential participants (e.g., medical condition, certain prescription medication). Does this apply to your study?

( ) Yes (•) No

If yes, please explain the exclusion criteria and the screening process.

Not that we are aware at this time.

3.6 Source of participants - Check all that apply:

Column A

- [ ] School Boards
- [ ] Correctional Services
- [ ] Agencies
- [ ] Mailing Lists
- [x] Businesses, Industries, Professions
- [ ] Hospitals, Long Term Care Facilities or other Health Care settings
- [x] Other - Please specify: Carleton University undergrad or graduate classes

Column B

- [x] uOttawa undergrad or graduate classes
- [ ] uOttawa Psychology ISPR
- [ ] Other uOttawa sources (e.g. Health Services Clinic, Pride Centre) - Please specify:

Indicate the specific names and locations of any sources checked (excluding Psychology ISPR):

Government of Canada/Department of National Defence employees

3.7 Who will be recruiting participants?

The primary investigator of this ethics submission: Daniel J. Kucherhan.

3.8 Are there any supervisory or trust-based relationships between persons conducting recruitment and the participants (e.g., professor-student, relative, friend, doctor-patient, therapist-client)?

(•) Yes ( ) No

If yes, describe the relationships and the steps that will be taken to ensure that there is no coercion.

Friendship between Daniel and one participant. Co-investigator will interact with this participant during experiments.

3.9 Describe how participants will be recruited. Please note that if participating organizations are being asked to distribute a recruitment invitation to potential participants, the researcher's contact information must appear on the recruitment invitation so that potential participants can contact the researcher directly.

Please append copies of all recruitment posters, advertisements, telephone scripts, letters of information, etc. that will be used for recruitment purposes.

Verbally in person, by providing a copy of the recruitment text. Should insufficient number of people be recruited verbally, the posters will be used to solicit further participants.

3.10 Is organizational or governmental permission needed to conduct research with the participants (e.g., school boards, employers, correctional services)?

○ Yes ◉ No

If yes, describe from whom permission is required and how this permission will be obtained. Include copies of all permissions.

3.11 Is research being conducted in another country?

○ Yes ◉ No

Please specify:

Is local ethical clearance needed to carry out the research?

◉ Yes ○ No

If no, explain the circumstances why ethical clearance is not required.

If yes, include copies of all approvals or explain how such approvals will be obtained

Through the uOttawa REB and sought from Carleton University if required.

PARTICIPATION

4.1 Describe what participants will be asked to do. Include how often participants will be asked to participate and how long each research activity will last. Please append any questionnaires, surveys, interview guides, focus group guides etc.

After explaining experimental procedures and obtaining informed-consent, seated participants will be asked to wear the prototype tactile feedback glove with or without an artificial attachment.

For phase 2 experiments, participants will be asked to close their eyes and describe the stimuli that they are feeling from the tactile feedback glove when presented with passive stimuli. For phase 3, seated participants will be asked to close their eyes and use only the prosthetic finger to identify mystery objects sequentially placed upon a table in front of them. For phase 4, seated participants will be presented with various handheld objects placed upon a table in front of them and asked to attempt grasping the object with their 'sixth' finger.

Participants will be asked to describe what they are feeling from the human tactile feedback glove and whether the 'sixth' finger is assisting them to grasp the objects presented. Each experimental phase will take no longer than 10 minutes to perform, with a mandatory 5 minute rest interval between phases. Participants will be asked to perform each phase a maximum of 3 times during one visit.

Experiments will take place at a workspace at the university of Ottawa (exact location TBD). Although data collection will be recorded ideally in one meeting, the analysis of the data that will take place subsequently by research investigators will continue following the completion of all experiments.

4.2 Provide the following details regarding the time and location of the data collection:

a) As relates to the specific participant population, describe when data collection will occur (e.g., interviews with school children will take place outside of class time; focus group sessions with professionals will take place during working hours).

Activities involving participants, including: consent briefing, experimental trial and recording of data will take place during normal weekly working hours (Monday - Friday, 0800-1800hrs daily). Exact time/date will be predetermined between both investigators and participant.

b) As relates to the specific participant population, describe the location of data collection (e.g., interviews with school children will take place in the library of John Smith Elementary School, located in Orleans, Ontario; focus group sessions will take place in a conference room in the John Smith office building located in Orleans, Ontario; interviews will take place in a coffee shop in Gatineau, Québec).

Activities involving participants will take place on university of Ottawa campus, within a common office workspace. Exact location to be selected.

4.3 Will scientific equipment involving direct or indirect physical contact be used (e.g., electrodes, sensory devices, probes)?

(•) Yes ( ) No

If yes, provide a description of the equipment and how it will be used.

A prototype tactile-feedback glove, developed by the aforementioned researchers, will be worn by participants. This glove will have an embedded tactile transducer array to convey pressure, a thermistor transducer for temperature and electro-vibrational unit for vibrational information to be relayed to the skin of the hand. The glove will be worn by participants who will describe the sensations they are feeling.

4.4 Does the research involve any invasive procedures whereby a scientific instrument, such as an esophageal probe, will be inserted into the body?

( ) Yes (•) No

If yes, who will be performing the procedure? Please provide appropriate clearance from the Office of Risk Management.

4.5 Will audio recording be used in the study?

( ) Yes (•) No

If yes, which research activity(s) will be audio recorded?

4.6 Will video recording or photography be used in the study?

(●) Yes ( ) No

If yes, which research activity(s) will be video recorded or photographed? If video recordings or photographs will be used in future presentations, for conference purposes, etc. please ensure that participants are aware of this and that permission is obtained and documented in the consent form.

Photographs of the experimental setup and prototype glove will be taken and may be used in presentations / papers. However, no personal information will be attached to any of the photographs. No photographs will be taken that reveal the identity of participants.

4.7 Will participants be compensated?

( ) Yes (●) No

If yes, provide details. Please note that since research participation is voluntary, participants are free to withdraw at any time without negative consequences. The Research Ethics Board requests that after a study has begun any participant who chooses to withdraw should still receive the compensation that had been offered. If for some reason participants will not be compensated after they have withdrawn from the study, please explain

5. ASSESSMENT OF RISKS

5.1 Indicate if the participants might experience any of the following:

	Yes	No
Risk of physical harm (e.g., falling, muscle pain)	☐	☒
Physical discomfort (e.g., tiredness, weakness, nausea)	☐	☒
Risk of psychological or emotional harm (e.g., trauma)	☐	☒
Psychological or emotional discomfort (e.g., anxiety, stress, loss of confidence, regret for disclosing personal information)	☐	☒
Legal repercussions for participating in the study (e.g., possibility of being sued, charged with criminal activity)	☐	☒
Social repercussions (e.g., possibility of marginalization, being negatively judged by peers or employer)	☐	☒
Economic inconveniences (e.g., expenses incurred for participation, loss of income during time of participation)	☐	☒
Other inconveniences (e.g., long travel to research site, time consumed, disruption of family routines)	☐	☒

5.2 If you answered yes to any of the items in section 5.1, please complete (a) and (b) below.

(a) Describe the risks, discomforts or inconveniences.

(b) Specify the measures taken to mitigate such risks, discomforts or inconveniences. Please include names and contact information of appropriate resources to which participants can be directed if needed.

6. BENEFITS

6.1 Describe the benefits of the research to the participants.

Participants will trial prototype advanced prosthetic devices that could lead to the availability of enhanced robotic and prosthetic tools.

6.2 Describe the benefits of the research to society.

Enhanced tactile feedback for remote operation of dexterous robotic hands, haptic sensing in virtual reality environments, advanced prosthetic design. Although the prototype designed by the aforementioned researchers will have a commercial value equal to the sum of its parts (<$500), intellectual property will reside with the developers of the prototype and the university of Ottawa.

7. PRIVACY OF PARTICIPANTS

Privacy concerns are strongest in regard to information that identifies a specific research participant. Collecting anonymous data is the most robust way of safeguarding the identity of research participants. Data which could enable the identification of participants, however, requires additional safeguards, such as removing identifiable information, using pseudonyms, or a code when working with the data and when disseminating research results. Particular attention is needed to ensure that participants in small communities or groups will be protected from inadvertent identification through a combination of identifiers such as date of birth, place of residence or unique personal characteristics.

7.1 Will any information be collected which would permit specific research participants to be identified through identifiers such as their name, address, social insurance number, personal health number, date of birth, place of residence, unique personal characteristic, etc.?

(●) Yes ( ) No

If yes, what identifiers will be collected?

Name, contact information (email/telephone number), sex, handedness, age, and if diagnosed with a tactile sensitivity disorder.

7.2 Please describe how the identity of the individuals will be safeguarded. If using pseudonyms or codes to remove identifiers, please describe who will have access to codes or pseudonyms to link data to participant identities.

An electronic file with participants' name, sex, handedness, age, tactile sensitivity disorder, and contact information and a unique identifiable code assigned to the participant will all be stored on removable media. At no time will the data contained within this protected file be stored on the same electronic media as research data. The unique identifiable code will be in the sole possession of the primary investigators of this study, and the unique identifiable code will be used in data file names. The four investigators listed in section 1 of this study will be the only people authorized to view the personal data file and only viewed if there is a need to know. Need to know decision will be taken by the custodian of the electronic file: the primary investigator.

7.3 Are there any conditions under which the protection of the identity of participants cannot or will not be guaranteed (e.g., participant chooses to be identified, members of a focus group)?

( ) Yes (●) No

If yes, please explain how this will be addressed and how participants will be informed of this.

7.4 When presenting the results of the research, will research participants be quoted?

( ) Yes (●) No

If yes, describe how identifying information will be removed or altered ensuring that quotes do not reveal individuals' identities. In the case where quotes will reveal individuals' identities, please explain the reasons and include this information in the consent form.

7.5 If research participants will be quoted, will they be given the opportunity to review their transcripts?

◯ Yes ◯ No ◉ Participants will not be quoted

If yes, please explain how research participants will have access to their transcripts. If sending transcripts via email, please explain the security measures being taken (e.g., encryption, password protection of documents). If no security measures are being contemplated, please inform research participants of the possible security risk in the consent form.

8. CONFIDENTIALITY OF DATA

The duty of confidentiality includes obligations to protect the data from unauthorized access, use, disclosure, modification, loss or theft. Researchers must provide details to the Research Ethics Board regarding their proposed measures for safeguarding information, for the full life cycle of information - that is, its collection, use, dissemination, retention and disposal. Physical safeguards include use of locked filing cabinets and location of computers containing research data away from public areas. Administrative safeguards include development and enforcement of organizational rules about who has access to personal information about research participants. Technical safeguards include use of computer passwords, firewall, anti-virus, encryption and other measures that protect data from unauthorized access, loss or modification.

Draft 2nd Edition of the Tri-Council Policy Statement: Ethics Conduct for Research Involving Humans
- Interagency Advisory Panel on Research Ethics - December 2008, p. 44

8.1 Who will conduct the data collection?

Data will be collected by one of the three research investigators identified in section 1. However, personal identifiers will be kept in a separate electronic file, in the custody of the primary investigator.

8.2 Who will have access to the data?

- [x] Principal Investigator
- [x] Thesis/Project Supervisor
- [x] Co-investigator
- [ ] Research Assistant
- [ ] Others (Please specify)

Any additional individuals who may have access to the data, who have not signed this form, such as research assistants, translators, interpreters, etc. must sign a confidentiality agreement.

8.3 Describe the physical (e.g., locked office) and technical (e.g., encryption) safeguards that will be used to securely store all sources of data, such as written records, electronic data, audio/video recordings, questionnaires, etc. during the course of the study.

All data will be recorded on university of Ottawa or personally owned equipment and stored in locked areas when not in the physical possession of one of the above listed investigators. Personal identifiable information of the participants will be in the sole custody of the primary investigator and password protected on removable media. All electronic file names that contain research data will have a uniquely identifiable code to preserve the anonymity of the participant.

8.4 Indicate how long data will be conserved and the starting time of the conservation period (e.g., following publication, completion of project). It is recommended that all data (excluding clinical trial data) be conserved for a minimum of 5 years. Clinical trial data must be stored for at least 25 years.

All data will be conserved by the principle investigator for 5 years following the study.

8.5 Describe how and where the data will be securely stored during the conservation period.

The data will be stored securely at the university of Ottawa under the custody of the thesis advisor listed in section 1 using removable media, in a locked filing cabinet, in a locked office.

8.6 Describe the methods of disposal for all types of data following the conservation period (e.g., shredding, secure deletion).

Physical media will be destroyed by shredding, electronic media will be securely deleted if possible, otherwise the electronic media will be wiped as per national prescribed guidelines.

9. FREE AND INFORMED CONSENT

Free and informed consent means that individuals agree to participate in research voluntarily and that each participant understands as fully as possible the purpose of the research, what is required of him/her, and the potential risks and benefits. When the participant population is comprised of both Francophones and Anglophones, the University of Ottawa Research Ethics Board requires that consent forms be provided in both French and English regardless of the language of the study, in order to ensure the greatest degree of understanding of what the research entails.

9.1 Describe the procedures that will be followed to obtain informed consent from the participant or legal guardian. Attach all consent documents, including information sheets and scripts.

Prospective participants who accept the conditions of the initial screening will then sign a written consent form as well as a secondary use of data form the same day that the data recordings will take place. See attached consent documents.

9.2 If written consent is not appropriate or cannot be obtained, describe why this is the case and how free and informed consent will be obtained and documented.

N/A, written consent will be obtained.

9.3 Who will be obtaining consent from the participants?

One of the three above-mentioned members of the research team will be obtaining consent from the participants. Completed consent forms, secondary use of data forms and debriefing forms will be held by the primary investigator.

9.4 Are there any supervisory or trust-based relationships between persons obtaining consent and the participants (e.g., professor-student, patient-doctor, relative, friend)?

(●) Yes ( ) No

If yes, please describe and explain the measures taken to ensure that participants do not feel pressure to participate or perceive they may be penalized for choosing not to participate.

!

Friend as described in section 3.8. There is already an understanding that if the friend does not wish to participate, they can leave the study at any time. Participation is strictly voluntary.

9.5 Does the project involve participants under the age of 18?

◯ Yes ◉ No

Please specify group:

If yes, consent from the parent or guardian is normally required. In addition, participants under the age of 18 should also be given the opportunity to agree to their involvement in the study. This is done with an age-appropriate assent text. Please attach a copy of the consent form and the assent form.

If an exception to this requirement is being sought, please explain.

9.6 Could participants feel pressure to participate or perceive that they may be penalized for choosing not to participate in the study?

◯ Yes ◉ No

If yes, please describe and explain the measures taken to ensure that participants do not feel pressure to participate or perceive they may be penalized for choosing not to participate.

9.7 Partial Disclosure/Deception: In certain research contexts, incomplete disclosure of relevant information or an element of deception is necessary for the successful conduct of the research. Will any of the procedures in this study include only partial disclosure of information to participants or an element of deception?

◯ Yes ◉ No

If yes, provide a rationale for the partial disclosure or element of deception. Include a description of the procedures for debriefing the participants and giving them an opportunity to consent to having their data remain in the study. If debriefing is not a viable option, please explain. If a participant's data cannot be removed from the study even when requested by the participant, please set out the conditions which make it impossible (e.g., part of a focus group)

10. SIGNATURES

I/we the undersigned, certify that:

(a) I/we have read the *Tri-Council Policy Statement: Ethical Conduct of Research Involving Humans* (TCPS 2, 2010);
(b) I/we have reviewed the application and are in agreement with the protocol as submitted;
(c) I/we will not commence with recruitment and data collection for the proposed research project until ethics approval has been granted;
(d) I/we will advise the Research Ethics Board of any revisions to the research arising before or after ethical approval is obtained;
(e) I/we have the responsibility to disclose to the Research Ethics Board real, perceived or potential conflicts of interest;
(f) I/we will not start the project, if funded by an external sponsor, until the contract/agreement has been approved by the appropriate university, hospital or research institute official.

Signature of the Principal Investigator

Date

Signature of the Thesis/Project Supervisor
(if applicable)

Date

Signature of the Co-investigator

Date

Signature of the Co-investigator

Date

Signature of the Co-investigator

Date

Remarks

Save as

Reset

Print

Appendix B – Research Ethics Board Approval Certificate

File Number: H08-16-13 | Date (mm/dd/yyyy): 12/13/2016

Université d'Ottawa | University of Ottawa

Bureau d'éthique et d'intégrité de la recherche | Office of Research Ethics and Integrity

Certificate of Ethics Approval

Health Sciences and Science REB

Principal Investigator / Supervisor / Co-investigator(s) / Student(s)

First Name	Last Name	Affiliation	Role
Emil	Petriu	Engineering / Electrical Engineering	Supervisor
Vinicius Prado	da Fonseca	Engineering / Electrical Engineering	Co-investigator
Miriam	Goubran	Health Sciences / Others	Co-investigator
Daniel J.	Kucherhan	Engineering / Others	Student Researcher

File Number: H08-16-13

Type of Project: Master's Thesis

Title: Tactile Feedback using Prosthetic/Robotic Fingers

Approval Date (mm/dd/yyyy)	Expiry Date (mm/dd/yyyy)
12/13/2016	12/12/2017

Special Conditions / Comments:
N/A

1

550, rue Cumberland | 550 Cumberland Street
Ottawa (Ontario) K1N 6N5 Canada | Ottawa, Ontario K1N 6N5 Canada
(613) 562-5387 • Téléc./Fax (613) 562-5338
http://www.recherche.uottawa.ca/deontologie/ | http://www.research.uottawa.ca/ethics/index.html

Université d'Ottawa
Bureau d'éthique et d'intégrité de la recherche
University of Ottawa
Office of Research Ethics and Integrity

This is to confirm that the University of Ottawa Research Ethics Board identified above, which operates in accordance with the Tri-Council Policy Statement and other applicable laws and regulations in Ontario, has examined and approved the application for ethical approval for the above named research project as of the Ethics Approval Date indicated for the period above and subject to the conditions listed the section above entitled "Special Conditions / Comments".

During the course of the study the protocol may not be modified without prior written approval from the REB except when necessary to remove participants from immediate endangerment or when the modification(s) pertain to only administrative or logistical components of the study (e.g. change of telephone number). Investigators must also promptly alert the REB of any changes which increase the risk to participant(s), any changes which considerably affect the conduct of the project, all unanticipated and harmful events that occur, and new information that may negatively affect the conduct of the project and safety of the participant(s). Modifications to the project, information/consent documentation, and/or recruitment documentation, should be submitted to this office for approval using the "Modification to research project" form available at: http://research.uottawa.ca/ethics/submissions-and-reviews.

Please submit an annual status report to the Protocol Officer 4 weeks before the above-referenced expiry date to either close the file or request a renewal of ethics approval. This document can be found at: http://research.uottawa.ca/ethics/submissions-and-reviews.

If you have any questions, please do not hesitate to contact the Ethics Office at extension 5387 or by e-mail at: ethics@uOttawa.ca.

Germain Zongo
Protocol Officer for Ethics in Research
For Daniel Lagarec, Chair of the Sciences and Health Sciences REB

550, rue Cumberland 550 Cumberland Street
Ottawa (Ontario) K1N 6N5 Canada Ottawa, Ontario K1N 6N5 Canada
(613) 562-5387 • Téléc./Fax (613) 562-5338
http://www.recherche.uottawa.ca/deontologie/ http://www.research.uottawa.ca/ethics/index.html

Appendix C – Consent Form & Participant Data Collection Form

uOttawa

Université d'Ottawa
Faculté de génie
École d'ingénierie et de technologie de l'information

University of Ottawa
Faculty of Engineering
School of Information Technology and Engineering

Informed Consent Form

Research Title: Tactile Feedback using Robotic/Prosthetic Fingers

This research project is being conducted by the following members of the University of Ottawa School of Information Technology and Engineering (SITE):

Principal investigator
-Mr Daniel Kucherhan

Supervisor
-Professor Emil Petriu, petriu@uottawa.ca, STE-5041, 800 King Edward, Ottawa, ON K1N 6N5, 613-562-5800 x2132.

Co-researcher
-Mr Vinicius da Fonseca

Co-researcher
-Mrs Miriam Goubran

Purpose: This informed consent form is to make sure that you understand the nature of your involvement in this study, and to obtain your informed consent to participate in this study.

Research Goal: The purpose of this study is to investigate how the highly sensitive tactile sensations normally felt in the human fingertip can best be remapped to a different part of the dermis on the hand. This non-invasive remapping will benefit those who wear a prosthetic or bionic finger, for those who seek to remotely operate assistive robotic fingers for dexterous manipulations, and may allow enhanced tactile feedback experience while interacting in the real world or in virtual reality environments.

Procedure: The experiments should take approximately sixty (60) minutes to complete. Seated in front of a table, you will be asked to put on the prototype tactile feedback glove. The experiment is divided into three parts:

Part 1: Remote tactile feedback from a hidden robotic fingertip.
Part 2: Prosthetic finger identification of an object/texture (blindfolded).
Part 3: Grasping and manipulation of objects using a 'sixth' finger.

During part 1, the robotic finger will be presented with various stimuli, such as hot or cold, a pin prick, as well as tactile cues such as tapping or images. You will be asked to describe what you are feeling from the glove at certain intervals.

Part 2 is meant for those who have lost a finger. A sensitive prosthetic finger will be worn by the gloved user who will then be blindfolded and asked to explore mystery objects placed upon the table in front of them using only the prosthetic.

613-562-5738
613-562-5664
800 King Edward (5105)
Ottawa ON K1N 6N5 Canada
www.uOttawa.ca

Part 3 of the experiment will involve exploring grasping and manipulation of objects, such as plastic bottles, using a glove that is fitted with a robotic 'sixth' finger.

Subject description: Healthy adult participants aged between 18 and 65 years.

Risks to participating: There are no known risk to health associated with this study.

Voluntary participation: Your participation in this study is voluntary. You may withdraw from the study at any time and/or refuse to respond to certain questions by verbally informing the investigator or any of the researchers, even after signing the consent form. There will be no negative consequences following any of these actions. Data collected from you will be subsequently deleted.

Secondary use of data collected: Data gathered may also be subject to future scientific studies and shall only be used for secondary purposes after once again obtaining your consent. Non-identifying images captured will be used in future presentations for conference purposes.

Compensation: There will be no compensation for participation in this study.

Confidentiality: Any information about you collected during the study will be kept strictly confidential. Your name will not be associated with the collected data in any way. While the results will appear in student's dissertations and may also be published in text or presentation format, you will not be identified.

Data collection and conservation: The data collection will be conducted by researcher of the University of Ottawa: Daniel J. Kucherhan, Vinicius Prado da Fonseca and/or Miriam Goubran. The records will be kept in electronic files on a laptop computer and the files will be protected. The data will be kept in Prof. Petriu's office when not in use and will be conserved for a minimum of 5 years, after which the computer files will be deleted and the consent forms will be shredded.

In closing: With your participation, you will be given a copy of this consent form. At the conclusion of the study, should you wish, you will be provided with a summary of the results. You may ask questions at any time, even after signing this consent form.

Signatures: I have read the above description of the study and understand the conditions of participation. My signature indicates that I agree to participate in the study.

If you have any concerns with regards to the ethical conduct of the study, you may contact the Protocol Officer for Ethics in Research, University of Ottawa, Tabaret Hall, 550 Cumberland Street, Room 154, Ottawa, ON, K1N 6N5, tel. (613) 562-5387, email: ethics@uottawa.ca.

Full Name of participant: ______________________________

Participant's Signature: ______________________________ **Date:**

Researcher's Signature: ______________________________ **Date:**

Page 2 of 2

Participant ID: ____________________

(5 mins) Consent Form signed? Y / N

(5 mins) **1.0 SENSORY TESTS:**

1.1 Subject's Feedback:

-Force Y / N

-Pressure Y / N

-Temp Y / N

******PREPARE PARTIPANT'S HAND FOR GLOVE******

1.2 Gloved subject receptive area on back of hand:

-Temperature (Hot) Y / N

-Temperature (Cold) Y / N

-Vibrational disks Y / N

(15 mins) **2.0 TRAINING:**

OPEN (All senses available to participant)

2.1 Passive touch

-Force Release Y / N

-Pressure Y / N

-Temp Y / N

2.2 Active touch single object exploration

Questions to participant:

-Did you feel anything? Y / N

-Can you describe what sensations you felt while exploring the object? (Temp, Vibrations, Edges, Features, etc)

____

____

____

____

Participant Initials: ____________________

Data Recorder Initials: ____________________ version 1.2

Participant ID: ______________________________

-Based upon the sensations, is it possible for you to identify the mystery object?

____

____

CLOSED (Auditory & Sight obstructed)

2.3 Passive touch

-Force Release Y / N

-Pressure Y / N

-Temp Y / N

2.4 Active touch single object exploration

Questions to participant:

-Did you feel anything? Y / N

-Can you describe what sensations you felt while exploring the object? (Temp, Vibrations, Edges, Features, etc)

____

____

____

____

-Based upon the sensations, is it possible for you to identify the mystery object?

____

____

Participant Initials: ____________________

Data Recorder Initials: ____________________

Participant ID: ______________________________

(30 mins) **3.0 EXPERIMENTS:**

3.1 Passive touch

3.1.1 1D Sensation identification (4 common materials)

Sensation 1: ______________. Correctly identified? Y / N

Sensation 2: ______________. Correctly identified? Y / N

Sensation 3: ______________. Correctly identified? Y / N

Sensation 4: ______________. Correctly identified? Y / N

Sensation 5: ______________. Correctly identified? Y / N

Sensation 6: ______________. Correctly identified? Y / N

3.2 Active touch

3.2.1 Common Object 1: ____________________ *(Most sensory modalities)*

Questions to participant:
-Did you feel anything? Y / N
-Can you describe what sensations you felt while exploring the object? (Temp, Vibrations, Edges, Features, etc)

____

____

____

____

-Based upon the sensations, is it possible for you to identify the mystery object?

____

____

3.2.2 Common Object 2: ____________________ *(Most sensory modalities)*

Questions to participant:
-Did you feel anything? Y / N

Participant Initials: __________________

Data Recorder Initials: __________________

Participant ID: ______________________________

-Can you describe what sensations you felt while exploring the object? (Temp, Vibrations, Edges, Features, etc)

____

____

____

____

-Based upon the sensations, is it possible for you to identify the mystery object?

____

____

3.2.3 Variable Object 3: ______________________

Questions to participant:
-Did you feel anything? Y / N
-Can you describe what sensations you felt while exploring the object? (Temp, Vibrations, Edges, Features, etc)

____

____

____

____

____

-Based upon the sensations, is it possible for you to identify the mystery object?

____

____

Participant Initials: ____________________

Data Recorder Initials: ____________________

Participant ID: ________________________________

DEBRIEF:

-How did the identification process go for you?

____

____

-How confident are you about the identification of each object?

____

____

-Show them the objects.

-What were some good aspects about the tactile feedback? What additional sensations do you think could be added to make the identification process better?

____

____

-Please do not reveal any of the details regarding the specific objects to your friends as they may be future participants.

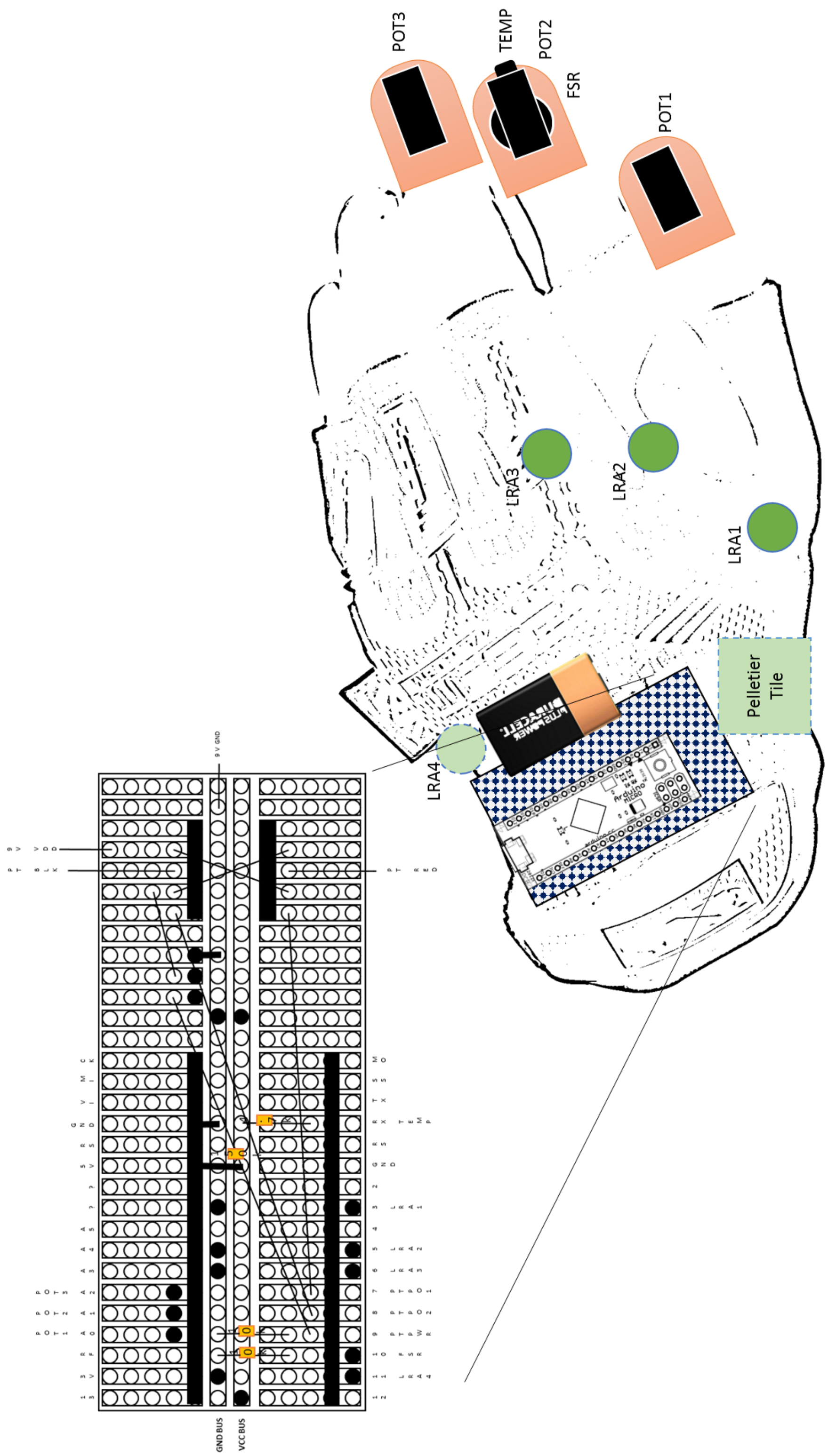
DATA RECORDED ON (Date/time):

____.

Participant Initials: ____________________

Data Recorder Initials: ____________________

Appendix D – Tactile Glove Wiring Diagram



Appendix E – Microcontroller Code, Arduino Integrated Development Environment (IDE)

```
/* Pro Micro / Tactile Feedback Module Test Code Prototype v1.0
 *  By: Daniel Kucherhan
 *  Date: 28 March 2017
 *  Description: This code controls the Pro Micro controller on the Tactile Glove Feedback Module. It
receives values from four types of sensors
 *  embedded within an artificial fingertip and activates two types of actuators to convey tactile
information to the user. Sensors are meant
 *  synthetically reproduce the mechano/thermo-receptor functionality located in a human fingertip and
were chosen specifically to capture the
 *  following four types of detectable tactile sensations: geo-specific force, pressure, vibration and
temperature. The actuators on the back
 *  of the tactile glove serve to remap the tactile sensations to be interpreted by its user. Three Linear
Resonating Actuators (LRA), also known
 *  as vibrating disks, convey the first three tactile sensations, while a Peltier Tile, also known as a
thermoelectric tile serves as the thermal
 *  actuator to convey temperature gradients.
 *
 *  Refs:
 *   1. Pro Micro Test Code, SparkFun Electronics.
 *   2. Pelletier Tile (www.customthermoelectric.com/tecs/pdf/12711-5L31-03CL_spec_sht.pdf)
 *   3. Linear Resonating Actuator (https://www.parallax.com/sites/default/files/downloads/28821-Flat-
Coin-Vibration-Motor-Documentation.pdf)
 *   4. Thin Potentiometer (http://www.spectrasymbol.com/potentiometer/thinpot/thinpot-datasheet)
 *   5. DS18B20 Temperature Sensors (datasheets.maximintegrated.com/en/ds/DS18B20.pdf)
 *   6. Monochrome OLED examples based on SSD1306 drivers, Written by Limor Fried/Ladyada for
Adafruit Industries
 *
 *   University of Ottawa 2016-2017, use of this code must include above references.
*/

#include <SPI.h>
#include <Wire.h>
#include <OneWire.h>
#include <Adafruit_GFX.h>
#include <Adafruit_SSD1306.h>

// PINOUT //

// SPI display settings
#define OLED_MOSI  16  //DATA or MOSI
#define OLED_CLK   15  //CLK or SCLK
#define OLED_DC    14  //DC or MISO  (NEED PWM?)
#define OLED_CS    2   //CS
#define OLED_RESET 4   //Rst
```

```
Adafruit_SSD1306 display(OLED_MOSI, OLED_CLK, OLED_DC, OLED_RESET, OLED_CS);

OneWire  ds1(0);  // DS18B20 Temperature sensor on wire bus embedded in fingertip
int LRA1 = 3;  //Linear resonating actuator (LRA) #1 connected to pin 3
int LRA2 = 5;  //Linear resonating actuator (LRA) #2 connected to pin 5
int LRA3 = 6;  //Linear resonating actuator (LRA) #3 connected to pin 6
int PTPO1 = 7; //Peltier Tile (PT) Polarity #1, to switch between heating and cooling on skin side of PT
int PTPO2 = 8; //Peltier Tile (PT) Polarity #2, to switch between heating and cooling on skin side of PT
int PTPWR = 9; //Peltier Tile (PT) Power Level (0 - 99%) connected to a N-type MOSFET
int FSR = 10;  //Force Sensing Resistor (FSR) embedded in fingertip (Detects fingertip pressure)
int POT1 = 18; //Thin potentiometer (POT) #1 embedded in fingertip (Detects fingertip force)
int POT2 = 19; //Thin potentiometer (POT) #2 embedded in fingertip (Detects fingertip force)
int POT3 = 20; //Thin potentiometer (POT) #3 embedded in fingertip (Detects fingertip force)
int VIBE = 21; //LDT0-028k Vibration sensor embedded in fingertip (Detects fingertip friction)

// VARIABLES //

int VIBEV, maxV1;            //Vibration sensor variables
float VIBEV1, maxVIBE5;
unsigned int FSRV, FSRV1;//FSR variable values
int POT1V, POT2V, POT3V; //POT# Variables to store the value read
int PTLVLV;            //Peltier Tile Level value
int PTLVLD;            //Display level value
boolean POL = LOW;      //Polarity toggle
int LRA1V, LRA2V, LRA3V; //LRA# Variables to store the intensity of the vibration
int LRA1D, LRA2D, LRA3D; //LRA# variables used to indicate appropriate level on display
int counter1 = 0;       //Temperature sensor delay counters
int TempConvDelay = 30;  //Temperature Conversion Delay counter, when the OneWire bus must
remain free of traffic, minimum 1000(ms) total, but 30ms with other executable code in runtime loop
float tempSens = 0.10;    //Temperature Sensistivity, determines difference between temp sensors to
cause Pelletier Tile to activate
float maxTempChg = 2.0;     //Maximum Power to PT will occur with a change in temperature of 2*C
float tempA,tempB,temp1 = 23.00;  //initialize temperature
float tempDiff = 0.0;
int ts1;              //Temperature sensor Display variable
char Lvl = ' ';        //Bar reading 'Level' display for sensors
boolean Display;  //Turns the display on/off

void setup(void) {
  Serial.begin(9600);

//Display SETUP
  // This will turn the display on or off
  Display = HIGH; //High is ON, LOW is OFF
```

```
  display.begin(SSD1306_SWITCHCAPVCC);
  // init done

  // Show image buffer on the display hardware.
  // Since the buffer is intialized with an Adafruit splashscreen
  // internally, this will display the splashscreen.
  display.display();
  delay(1000);
  testscrolltext();

  // invert the display
  display.invertDisplay(true);
  delay(500);
  display.invertDisplay(false);
  delay(500);

  // Clear the buffer.
  display.clearDisplay();

  // text display tests
  display.setTextSize(1);
  display.setTextColor(WHITE);
  display.setCursor(0,0);
  display.println("    TACTILE GLOVE");
  display.println();  display.println(); display.println();
  display.println("    D.J. Kucherhan");
  display.println();  display.println();
  display.setTextColor(BLACK, WHITE); // 'inverted' text
  display.println("  (C) uOTTAWA 2017  ");
  display.println();
  display.display();
  delay(6000);
  display.clearDisplay();

//pinMode SETUP

  pinMode(PTPO1, OUTPUT); //sets pin 7 as output
  pinMode(PTPO2, OUTPUT); //sets pin 8 as output
  pinMode(PTPWR, OUTPUT); //sets pin 9 as output (analog - PWM)
  pinMode(LRA1, OUTPUT);  //sets pin 3 as an output (analog - PWM)
  pinMode(LRA2, OUTPUT);  //sets pin 5 as an output (analog - PWM)
  pinMode(LRA3, OUTPUT);  //sets pin 6 as an output (analog - PWM)
  pinMode(FSR, INPUT);    //sets pin 10 as an input (analog)
  pinMode(POT1, INPUT);   //sets pin 18 as an input (analog)
  pinMode(POT2, INPUT);   //sets pin 19 as an input (analog)
```

```
  pinMode(POT3, INPUT);   //sets pin 20 as an input (analog)
  pinMode(VIBE, INPUT);   //sets pin 21 as an input
  digitalWrite(PTPWR, LOW);  //initial PT setting
  digitalWrite(PTPO1, LOW);  //initial Polarity setting
  digitalWrite(PTPO2, LOW);  //initial Polarity setting
  digitalWrite(POT1, HIGH);  //pullup resistor for stability
  digitalWrite(POT2, HIGH);  //pullup resistor for stability
  digitalWrite(POT3, HIGH);  //pullup resistor for stability
  //digitalWrite(FSR, HIGH);   //pullup resistor for stability
  //digitalWrite(VIBE, HIGH);  //pullup resistor for stability
}


void loop(void) {
  byte i;
  byte present = 0;
  byte data[12];
 // byte addr1[8] = {0x28, 0x7E, 0xB8, 0x8A, 0x08, 0x00, 0x00, 0x03}; //address of sensor 1 (on sensor
display module)
  byte addr1[8] = {0x28, 0x21, 0x11, 0xBB, 0x08, 0x00, 0x00, 0x0E}; //address of sensor 2 (embedded in
black-cabled fingertip module)
 // byte addr3[8] = {0x28, 0x06, 0xD0, 0xBB, 0x08, 0x00, 0x00, 0xD2}; //address of sensor 3
 // byte addr4[8] = {0x28, 0xEF, 0x15, 0xBB, 0x08, 0x00, 0x00, 0x9D}; //address of sensor 4
 // byte addr5[8] = {0x28, 0xCE, 0x77, 0xB9, 0x08, 0x00, 0x00, 0x89}; //address of sensor 5


//2x DS18B20, TEMPERATURE SENSORS CODE:
//Temperature Sensor addr1 conversion
  if (counter1 == 0) {
    ds1.reset();
    ds1.select(addr1);
    ds1.write(0x44,1);        // start conversion, with parasite power on at the end
    //delay(750);             // maybe 750ms is enough, maybe not
    counter1 = TempConvDelay;
  }
  if (counter1 > 0) {
    counter1--;
  }
  //Serial.print("Counter1 is ");
  //Serial.println(counter1);

//Temperature Sensor addr1 read and convert temperature
  if (counter1 == 0) {
    tempB = tempA;
    tempA = temp1;
```

```
  present = ds1.reset();
  ds1.select(addr1);
  ds1.write(0xBE);        // Read Scratchpad
  for ( i = 0; i < 9; i++) {        // we need 9 bytes
    data[i] = ds1.read(); }
  temp1 = ( (data[1] << 8) + data[0] )*0.0625;  //calculate temperature value
  Serial.print("The temperature reading of addr1 is ");
  Serial.print(temp1);
  Serial.println(" *C");
  counter1 = 0; }

/*

//Temperature Sensor addrX conversion
 if ( (counter1 == 0) && (counter2 == 0) ) {
  ds1.reset();
  ds1.select(addrX);
  ds1.write(0x44,1);        // start conversion, with parasite power on at the end
  //delay(250);              // maybe 750ms is enough, maybe not
  counter2 = TempConvDelay;
 }
 if (counter2 > 0) {
  counter2--;
 }
 //Serial.print("Counter2 is ");
 //Serial.println(counter2);

//Temperature Sensor addr2 read and convert temperature
 if ((counter1 == 0) && (counter2 == 0)) {
  present = ds1.reset();
  ds1.select(addrX);
  ds1.write(0xBE);        // Read Scratchpad
  for ( i = 0; i < 9; i++) {          // we need 9 bytes
    data[i] = ds1.read(); }
  temp2 = ( (data[1] << 8) + data[0] )*0.0625;  //calculate temperature value
  //Serial.print("The temperature reading of addr2 is ");
  //Serial.print(temp2);
  //Serial.println(" *C");
  counter2 = 0; }

*/
 if(millis() > 20000) { //allows temp sensor to bootup at startup
    tempDiff = temp1 - tempA;
    //Serial.print("temp1 - temp2 = ");
    //Serial.println(tempDiff);
```

```
 }


 //DISPLAY CODE:
 if(Display == HIGH){
   display.setTextSize(1);
   display.setTextColor(WHITE);
   display.setCursor(0,0);
   display.print("Force Centre:"); display.setTextColor(BLACK, WHITE); for(; LRA1D > 0; LRA1D--
){display.print(Lvl);} display.println(); display.setTextColor(WHITE);
   display.print("Force Left  :"); display.setTextColor(BLACK, WHITE); for(; LRA2D > 0; LRA2D--
){display.print(Lvl);} display.println(); display.setTextColor(WHITE);
   display.print("Force Right :"); display.setTextColor(BLACK, WHITE); for(; LRA3D > 0; LRA3D--
){display.print(Lvl);} display.println(); display.setTextColor(WHITE);
   display.print("Temp      : "); display.print(temp1); display.write(247); display.print("C");
display.println();   //247 is the degree symbol
   display.print("Temp Chg  : "); if(tempDiff >= 0.0){display.write(43);} display.print(tempDiff);
display.write(247); display.print("C"); display.println(); //display.println();
   display.print("Peltier Tile:"); if((PTLVLD > 0) && (POL == HIGH)){ for(; PTLVLD > 0; PTLVLD--
){display.write(24);display.write(24);display.write(24);}} if((PTLVLD > 0) && (POL == LOW)){ for(; PTLVLD
> 0; PTLVLD--){display.write(25);display.write(25);display.write(25);}} display.println();
   display.print("Pressure  : "); display.setTextColor(BLACK, WHITE); for(; FSRV > 1; FSRV--
){display.print(Lvl);} display.println(); display.setTextColor(WHITE);
   display.print("Texture   : "); display.print(maxVIBE5); //display.println(VIBEV1);
 }
 display.display();
 display.clearDisplay();


//PELLETIER TILE (PT) CODE:
 if ((tempDiff > tempSens)) {   // && (temp1 < maxTemp) && (temp1 > minTemp)) {
  //DEBUG:
   Serial.print("tempDiff: ");
   Serial.print(tempDiff);
   tempDiff = constrain(tempDiff, tempSens, maxTempChg);  // constrains tempDiff between tempSens
and 2
   PTLVLV = map(tempDiff, tempSens, maxTempChg, 0, 255);  // Power level mapped from tempDiff
   PTLVLD = (int)tempDiff;                              // display level
   if(POL == LOW){
     digitalWrite(PTPO1, HIGH);    // polarity for relay/PT (HEAT)
     delay(15);                  // relay requires 15 second min pulse to latch in position
     digitalWrite(PTPO1, LOW);     // once relay is latched, power can be removed and latch remains in
position
     POL = HIGH;
   }
```

```
   analogWrite(PTPWR, PTLVLV);   // Power the PT
  //DEBUG:
  //  Serial.print("    Modified tempDiff: ");
  //  Serial.println(tempDiff);
  //  Serial.print("PTLVLV: ");
  //  Serial.print(PTLVLV);
  //  Serial.print("    TEMP1: ");
  //  Serial.print(temp1);
  //  Serial.print("    TEMPA: ");
  //  Serial.print(tempA);
  //  Serial.print("    TEMPB: ");
  //  Serial.println(tempB);
   }
  else if ((tempDiff < -tempSens)) { // && (temp1 < maxTemp) && (temp1 > minTemp)) {
   //DEBUG:
   Serial.print("tempDiff: ");
   Serial.print(tempDiff);
   tempDiff = abs(tempDiff);
   tempDiff = constrain(tempDiff, tempSens, maxTempChg);
   PTLVLV = map(tempDiff, tempSens, maxTempChg, 0, 255);  // Power level mapped from tempDiff
   PTLVLD = (int)tempDiff;                              // display level
   if(POL == HIGH){
     digitalWrite(PTPO2, HIGH);    // polarity for relay/PT (COOLING)
     delay(15);                  // relay requires 15 second min pulse to latch in position
     digitalWrite(PTPO2, LOW);     // once relay is latched, power can be removed and latch remains in
position
     POL = LOW;
   }
   analogWrite(PTPWR, PTLVLV);   // Power the PT
  //DEBUG:
  //  Serial.print("    Modified tempDiff: ");
  //  Serial.println(tempDiff);
  //  Serial.print("PTLVLV: ");
  //  Serial.print(PTLVLV);
  //  Serial.print("    TEMP1: ");
  //  Serial.print(temp1);
  //  Serial.print("    TEMPA: ");
  //  Serial.print(tempA);
  //  Serial.print("    TEMPB: ");
  //  Serial.println(tempB);
   }
  else {
   PTLVLV = 0;
   PTLVLD = 0;
   analogWrite(PTPWR, PTLVLV);  //off
```

```
   digitalWrite(PTPO1, LOW);    //just in case
   digitalWrite(PTPO2, LOW);    //just in case
 //DEBUG:
 //  Serial.print("PT OFF....PTLVLV:  ");
 //  Serial.print(PTLVLV);
 //  Serial.print("    TEMP1: ");
 //  Serial.print(temp1);
 //  Serial.print("    TEMPA: ");
 //  Serial.print(tempA);
 //  Serial.print("    TEMPB: ");
 //  Serial.println(tempB);
   }

//POTENTIOMETER (POT) CODE:
//Read the Thin Potentiometer values
  POT1V = 1023 - analogRead(POT1);   //read the input, returns values 0-1023, increments of 4.9mV,
read every 100us, mod with analogReference()
  //Serial.print("POT1V: ");
  //Serial.println(POT1V);      //debug POT1 value

  POT2V = 1023 - analogRead(POT2);   //read the input, returns values 0-1023, increments of 4.9mV,
read every 100us, mod with analogReference()
  //Serial.print("POT2V: ");
  //Serial.println(POT2V);      //debug POT1 value

  POT3V = 1023 - analogRead(POT3);   //read the input, returns values 0-1023, increments of 4.9mV,
read every 100us, mod with analogReference()
  //Serial.print("POT3V: ");
  //Serial.println(POT3V);      //debug POT1 value

//Convert POT values into Linear Resonating Actuators (LRA) intensity values
  LRA1V = map(POT2V, 1000, 100, 0, 255);  //convert the POT value into LRA intensity
  //LRA1V = constrain(LRA1V, 0, 255);
  //Serial.print("LRA1V: ");
  //Serial.println(LRA1V);      //debug
  if(LRA1V < 256) {
    LRA1D = map(LRA1V, 0, 255, 0, 8); // 8 incremental levels on the display
   // Serial.print("LRA1D: ");
   // Serial.println(LRA1D);      //debug
  }

  LRA2V = map(POT3V, 1000, 100, 0, 255);  //convert the POT value into LRA intensity
  //LRA2V = constrain(LRA2V, 0, 255);
  //Serial.print("LRA2V: ");
  //Serial.println(LRA2V);      //debug
```

```
 if(LRA2V < 256) {
   LRA2D = map(LRA2V, 0, 255, 0, 8); // 8 incremental levels on the display
  // Serial.print("LRA2D: ");
  // Serial.println(LRA2D);     //debug
  }

 LRA3V = map(POT1V, 1000, 100, 0, 255);  //convert the POT value into LRA intensity
 //LRA3V = constrain(LRA3V, 0, 255);
 //Serial.print("LRA3V: ");
 //Serial.println(LRA3V);     //debug
  if(LRA3V < 256) {
   LRA3D = map(LRA3V, 0, 255, 0, 8); // 8 incremental levels on the display
  // Serial.print("LRA3D: ");
  // Serial.println(LRA3D);     //debug
  }

//Activate LRAs
 analogWrite(LRA1, LRA1V);   //LRA will vibrate with PWM value between 0-255 depending on POT
voltage value
 analogWrite(LRA2, LRA2V);   //LRA will vibrate with PWM value between 0-255 depending on POT
voltage value
 analogWrite(LRA3, LRA3V);   //LRA will vibrate with PWM value between 0-255 depending on POT
voltage value

//VIBRATION SENSOR (LDT0-028K) CODE:
//Read the sensor value
   VIBEV = 8 - analogRead(VIBE) / 5;  //read sensor
   VIBEV1 = abs(VIBEV);
   maxVIBE5 = max(VIBEV1, maxVIBE5);
  // Serial.print("maxVIBE5: ");
  // Serial.println(maxVIBE5);     //debug maxVIBE5 value
   maxVIBE5 = constrain(maxVIBE5, 1.0, 30.00);
   maxV1 = map(maxVIBE5, 1.0, 30.00, 0, 255); //map vibe values
 //  Serial.print("maxV1: ");
 //  Serial.println(maxV1);     //debug maxVIBE5 value
   /////analogWrite(LRA3, maxV1);
   if(counter1 % 10 == 1){
     maxVIBE5 = 1.0;
   }


//FORCE SENSOR RESISTOR (FSR) CODE:
//Read the sensor value
 FSRV = analogRead(FSR) / 100;   //read the input, returns values 0-1023, increments of 4.9mV, read
every 100us, mod with analogReference()
```

```
 FSRV1 = map(FSRV, 0, 9, 0, 255);
 //analogWrite(LRA1, FSRV1);
 //analogWrite(LRA3, FSRV1);
 //Serial.println(FSRV);     //debug FSRV

} //end loop


//SUB-PROTOCOLS
void testscrolltext(void) {
 display.startscrollright(0x00, 0x0F);
 delay(8000);
 display.stopscroll();
 delay(1000);
}
```

```
/* Genuino Micro / Tactile Feedback Module Test Code Prototype v2.0
 *  By: Daniel Kucherhan
 *  Date: 24 April 2017
 *  Description: This code controls the Genuino Micro controller on the Tactile Glove Feedback Module. It receives values from three types of sensors
 *  embedded within an artificial fingertip and activates two types of actuators to convey tactile information to the user. Sensors are meant
 *  synthetically reproduce the mechano/thermo-receptor functionality located in a human fingertip and were chosen specifically to capture the
 *  following three types of detectable tactile sensations: geo-specific force, pressure, and temperature. The actuators embedded within the insides
 *  of the tactile glove serve to remap the tactile sensations to be interpreted by its user. Four Linear Resonating Actuators (LRA), also known
 *  as vibrating disks, convey the first two tactile sensations, while a Peltier Tile, also known as a thermoelectric tile serves as the thermal
 *  actuator to convey temperature gradients.
 *
 *  Refs:
 *   1. Arduino Genuino Micro (https://www.arduino.cc/en/Main/ArduinoBoardMicro).
 *   2. Pelletier Tile (www.customthermoelectric.com/tecs/pdf/12711-5L31-03CL_spec_sht.pdf)
 *   3. Linear Resonating Actuator (https://www.parallax.com/sites/default/files/downloads/28821-Flat-Coin-Vibration-Motor-Documentation.pdf)
 *   4. Thin Potentiometer (http://www.spectrasymbol.com/potentiometer/thinpot/thinpot-datasheet)
 *   5. DS18B20 Temperature Sensors (datasheets.maximintegrated.com/en/ds/DS18B20.pdf)
 *
 *   University of Ottawa 2016-2017, use of this code must include above references.
*/

#include <SPI.h>
```

```
#include <Wire.h>
#include <OneWire.h>


// PINOUT //

OneWire  ds1(0);  // DS18B20 Temperature sensor on wire bus embedded in fingertip
int LRA1 = 3;  //Linear resonating actuator (LRA) #1 connected to pin 3
int LRA2 = 5;  //Linear resonating actuator (LRA) #2 connected to pin 5
int LRA3 = 6;  //Linear resonating actuator (LRA) #3 connected to pin 6
int LRA4 = 11; //Linear resonating actuator (LRA) #4 connected to pin 11
int PTPO1 = 7; //Peltier Tile (PT) Polarity #1, to switch between heating and cooling on skin side of PT
int PTPO2 = 8; //Peltier Tile (PT) Polarity #2, to switch between heating and cooling on skin side of PT
int PTPWR = 9; //Peltier Tile (PT) Power Level (0 - 99%) connected to a N-type MOSFET
int FSR = 10;  //Force Sensing Resistor (FSR) embedded in fingertip (Detects fingertip pressure)
int POT1 = A0; //Thin potentiometer (POT) #1 embedded in fingertip (Detects fingertip force)
int POT2 = A1; //Thin potentiometer (POT) #2 embedded in fingertip (Detects fingertip force)
int POT3 = A2; //Thin potentiometer (POT) #3 embedded in fingertip (Detects fingertip force)

// VARIABLES //

unsigned int FSRV, FSRV1; //FSR variable values
int POT1V, POT2V, POT3V, POT1A, POT2A, POT3A, POT1B, POT2B, POT3B; //POT# Variables to store the
value read
int PTLVLV;              //Peltier Tile (PT) Level value
boolean POL = LOW;       //Polarity toggle for PT
boolean DEBUG = FALSE;    //Debugging mode TRUE or FALSE to display info in serial monitor
boolean REPORT = TRUE;    //Allows data to be printed out to the serial monitor for data reporting
purposes
int LRA1V, LRA2V, LRA3V, LRA1C, LRA2C, LRA3C; //LRA# Variables to store the intensity of the vibration
int counter1 = 0;        //Temperature sensor delay counters
int TempConvDelay = 1200; //Temperature Conversion Delay counter, when the OneWire bus must
remain free of traffic, minimum 1000(ms) total, but 30ms with other executable code in runtime loop
//TempConvDelay without Serial Monitor must be a minimum of 1200. If Serial Monitor is not running
then it must be a minimum of 300.
float tempSens = 0.20;    //Temperature Sensistivity, determines difference between temp sensors to
cause Pelletier Tile to activate
float maxTempChg = 2.0;   //Maximum Power to PT will occur with a change in temperature of 2*C
float tempA,temp1;       //initialize temperature variables
float tempDiff;
int power = 0; //Power level from -50 to 50
int peltier_level; //PT level from -50 to 50

void setup(void) {
  Serial.begin(9600);
```

```
//pinMode SETUP

  pinMode(PTPO1, OUTPUT); //sets pin 7 as output
  pinMode(PTPO2, OUTPUT); //sets pin 8 as output
  pinMode(PTPWR, OUTPUT); //sets pin 9 as output (analog - PWM)
  pinMode(LRA1, OUTPUT);  //sets pin 3 as an output (analog - PWM)
  pinMode(LRA2, OUTPUT);  //sets pin 5 as an output (analog - PWM)
  pinMode(LRA3, OUTPUT);  //sets pin 6 as an output (analog - PWM)
  pinMode(LRA4, OUTPUT);  //sets pin 11 as an output (analog - PWM)
  pinMode(FSR, INPUT);    //sets pin 10 as an input (analog)
  pinMode(POT1, INPUT);   //sets pin 18 as an input (analog)
  pinMode(POT2, INPUT);   //sets pin 19 as an input (analog)
  pinMode(POT3, INPUT);   //sets pin 20 as an input (analog)
  digitalWrite(PTPWR, LOW);  //initial PT setting
  digitalWrite(PTPO1, LOW);  //initial Polarity setting
  digitalWrite(PTPO2, LOW);  //initial Polarity setting
  digitalWrite(POT1, HIGH);  //pullup resistor for stability
  digitalWrite(POT2, HIGH);  //pullup resistor for stability
  digitalWrite(POT3, HIGH);  //pullup resistor for stability
}  //end setup


void loop(void) {
  byte i;
  byte present = 0;
  byte data[12];
 // byte addr1[8] = {0x28, 0x7E, 0xB8, 0x8A, 0x08, 0x00, 0x00, 0x03}; //address of sensor 1 (on sensor
display module)
  byte addr1[8] = {0x28, 0x21, 0x11, 0xBB, 0x08, 0x00, 0x00, 0x0E}; //address of sensor 2 (embedded in
black-cabled fingertip module)
 // byte addr3[8] = {0x28, 0x06, 0xD0, 0xBB, 0x08, 0x00, 0x00, 0xD2}; //address of sensor 3 (embedded
in prototype v2.0 fingertip)
 // byte addr4[8] = {0x28, 0xEF, 0x15, 0xBB, 0x08, 0x00, 0x00, 0x9D}; //address of sensor 4
 // byte addr5[8] = {0x28, 0xCE, 0x77, 0xB9, 0x08, 0x00, 0x00, 0x89}; //address of sensor 5
  char option;

//2x DS18B20, TEMPERATURE SENSORS CODE:
//Temperature Sensor addr1 conversion
  if (counter1 == 0) {
    ds1.reset();
    ds1.select(addr1);
    ds1.write(0x44,1);        // start conversion, with parasite power on at the end
    //delay(750);
    counter1 = TempConvDelay;
```

```
 }
 if (counter1 > 0) {
  counter1--;
 }
 if(DEBUG == TRUE){
  Serial.print("Counter1 is ");
  Serial.println(counter1);
 }


//Temperature Sensor addr1 read and convert temperature
 if (counter1 == 0) {
  tempA = temp1;
  present = ds1.reset();
  ds1.select(addr1);
  ds1.write(0xBE);        // Read Scratchpad
  for ( i = 0; i < 9; i++) {        // we need 9 bytes
   data[i] = ds1.read(); }
  temp1 = ( (data[1] << 8) + data[0] )*0.0625;  //calculate temperature value
  if((DEBUG == TRUE)||(REPORT == TRUE)){
   Serial.print("The temperature reading of temp1 is ");
   Serial.print(temp1);
   Serial.println(" *C");
  }
  counter1 = 0; }



 if(millis() > 2000) { //allows temp sensor to bootup at startup
  tempDiff = temp1 - tempA;
  if(DEBUG == TRUE){
   Serial.print("TempDiff = temp1 - tempA = ");
   Serial.println(tempDiff);
  }
 }
 else {
  tempA = temp1;
 }

//OPTIONAL RAISE TEMP MANUALLY
 if(Serial.available() > 0){
  option = Serial.read();
  if(option == 'a')
   power += 5;
  else if(option == 'z')
```

```
    power -= 5;
  else if(option == 'p')
    power = 0;

  if(power > 50) power = 50;
  if(power < -50) power = -50;

  peltier_level = power; //map(power, 0, 99, 0, 99);

  if((option == 'a')||(option == 'z')||(option == 'p')){
    Serial.print("Peltier Tile Manually Activated:");
    Serial.print("  option=");
    Serial.print(option);
    Serial.print("  Power=");
    Serial.print(power);
    Serial.print("  PLevel=");
    Serial.println(peltier_level);
  }
 }

//PELTIER TILE (PT) CODE:
 if ((tempDiff > tempSens)||(peltier_level > 0)) {   // && (temp1 < maxTemp) && (temp1 > minTemp)) {
  if((DEBUG == TRUE)||((REPORT == TRUE)&&(counter1 == 0))){
    Serial.print("Peltier Tile is HEATING....tempDiff: ");
    Serial.println(tempDiff);
  }
  tempDiff = constrain(tempDiff, tempSens, maxTempChg);  // constrains tempDiff between
tempSensitivity and maxTempChg
  PTLVLV = tempDiff*100;     //Power level mapped from tempDiff
  if(peltier_level > 0){     //Manually activated PT level using keyboard inputs
    PTLVLV = map(peltier_level,1,50,1,255);
  }
  if(POL == LOW){
    digitalWrite(PTPO1, HIGH);    // polarity for relay/PT (HEAT)
    delay(15);                    // relay requires 15 second min pulse to latch in position
    digitalWrite(PTPO1, LOW);     // once relay is latched, power can be removed and latch remains in
position
    POL = HIGH;
  }
  analogWrite(PTPWR, PTLVLV);   // Power the PT
  if(DEBUG == TRUE){
    Serial.print("    Modified tempDiff: ");
    Serial.println(tempDiff);
    Serial.print("PTLVLV: ");
    Serial.print(PTLVLV);
```

```
    Serial.print("    TEMP1: ");
    Serial.print(temp1);
    Serial.print("    TEMPA: ");
    Serial.print(tempA);
   }
  }
  else if ((tempDiff < -tempSens)||(peltier_level < 0)) {
   if((DEBUG == TRUE)||((REPORT == TRUE)&&(counter1 == 0))){
    Serial.print("Peltier Tile is COOLING....tempDiff: ");
    Serial.println(tempDiff);
   }
   tempDiff = abs(tempDiff);
   tempDiff = constrain(tempDiff, tempSens, maxTempChg);   // constrains tempDiff between
tempSensitivity and maxTempChg
   PTLVLV = tempDiff*100;     //Power level mapped from tempDiff
   if(peltier_level < 0){     //Manually activated PT level using keyboard inputs
    PTLVLV = map(peltier_level,-1,-50,1,255);
   }
   if(POL == HIGH){
    digitalWrite(PTPO2, HIGH);    // polarity for relay/PT (COOLING)
    delay(15);                  // relay requires 15 second min pulse to latch in position
    digitalWrite(PTPO2, LOW);     // once relay is latched, power can be removed and latch remains in
position
    POL = LOW;
   }
   analogWrite(PTPWR, PTLVLV);   // Power the PT
   if(DEBUG == TRUE){
    Serial.print("    Modified tempDiff: ");
    Serial.println(tempDiff);
    Serial.print("PTLVLV: ");
    Serial.print(PTLVLV);
    Serial.print("    TEMP1: ");
    Serial.print(temp1);
    Serial.print("    TEMPA: ");
    Serial.print(tempA);
   }
  }
  else {
   PTLVLV = 0;
   analogWrite(PTPWR, PTLVLV);  //off
   digitalWrite(PTPO1, LOW);    //just in case
   digitalWrite(PTPO2, LOW);    //just in case
   if(DEBUG == TRUE){
    Serial.print("PT OFF....PTLVLV:  ");
    Serial.print(PTLVLV);
```

```
    Serial.print("    TEMP1: ");
    Serial.print(temp1);
    Serial.print("    TEMPA: ");
    Serial.println(tempA);
   }
  }


//POTENTIOMETER (POT) CODE:
//Read the Thin Potentiometer values
  POT1V = analogRead(POT1);   //read the input, returns values 0-1023, increments of 4.9mV, read every
100us, mod with analogReference()
  if((DEBUG == TRUE)||((REPORT == TRUE)&&(counter1 == 0))){
    Serial.print("POT1V: ");
    Serial.println(POT1V);      //debug POT1 value
  }

  POT2V = analogRead(POT2);   //read the input, returns values 0-1023, increments of 4.9mV, read every
100us, mod with analogReference()
  if((DEBUG == TRUE)||((REPORT == TRUE)&&(counter1 == 0))){
    Serial.print("POT2V: ");
    Serial.println(POT2V);      //debug POT1 value
  }

  POT3V = analogRead(POT3);   //read the input, returns values 0-1023, increments of 4.9mV, read every
100us, mod with analogReference()
  if((DEBUG == TRUE)||((REPORT == TRUE)&&(counter1 == 0))){
    Serial.print("POT3V: ");
    Serial.println(POT3V);      //debug POT1 value
  }

//Convert POT values into Linear Resonating Actuators (LRA) intensity values
  POT1B = POT1A;
  POT1A = POT1V;
  if((POT1V - POT1B) > 60){  //rapidly decreasing POT1 gradient will cause a burst vibration in the
corresponding LRA
    LRA1V = 455;
  }
  //else if ((POT1V - POT1B) > 10){
  //  LRA1V = 165;
  //}
  else if(LRA1V > 0){          //LRA vibration intensity will rapidly decrease thereafter
    LRA1V = LRA1V - 1;
  }
  else{                        //Otherwise, no vibration
```

```
    LRA1V = 0;
  }
  if(DEBUG == TRUE){
    Serial.print("POT1V: ");
    Serial.print(POT1A);
    Serial.print("  POT1A: ");
    Serial.print(POT1A);
    Serial.print("  POT1B: ");
    Serial.println(POT1B);
    Serial.print("  **************LRA1V: ");
    Serial.println(LRA1V);
  }

  POT2B = POT2A;
  POT2A = POT2V;
  if((POT2V - POT2B) > 25){  //rapidly decreasing POT1 gradient will cause a burst vibration in the
corresponding LRA
    LRA2V = 455;
  }
  //else if ((POT2V - POT2B) > 60){
  //  LRA2V = 165;
  //}
  else if(LRA2V > 0){          //LRA vibration intensity will rapidly decrease thereafter
    LRA2V = LRA2V - 1;
  }
  else{                        //Otherwise, no vibration
    LRA2V = 0;
  }
  if(DEBUG == TRUE){
    Serial.print("POT2V: ");
    Serial.print(POT2A);
    Serial.print("  POT2A: ");
    Serial.print(POT2A);
    Serial.print("  POT2B: ");
    Serial.println(POT2B);
    Serial.print("  **************LRA2V: ");
    Serial.println(LRA2V);
  }

  POT3B = POT3A;
  POT3A = POT3V;
  if((POT3V - POT3B) > 100){  //rapidly decreasing POT1 gradient will cause a burst vibration in the
corresponding LRA
    LRA3V = 355;
  }
```

```
  //else if ((POT3V - POT3B) > 0){
  //  LRA3V = 165;
  //}
  else if(LRA3V > 0){          //LRA vibration intensity will rapidly decrease thereafter
    LRA3V = LRA3V - 1;
  }
  else{                       //Otherwise, no vibration
    LRA3V = 0;
  }
  if(DEBUG == TRUE){
    Serial.print("POT3V: ");
    Serial.print(POT3A);
    Serial.print("  POT3A: ");
    Serial.print(POT3A);
    Serial.print("  POT3B: ");
    Serial.println(POT3B);
    Serial.print("  **************LRA3V: ");
    Serial.println(LRA3V);
  }



/*
//Convert POT values into Linear Resonating Actuators (LRA) intensity values
  LRA1V = map(POT1V, 1000, 100, 0, 255);  //convert the POT value into LRA intensity
  //LRA1V = constrain(LRA1V, 0, 255);
  if((DEBUG == TRUE)||((REPORT == TRUE)&&(counter1 == 0))){
    Serial.print("LRA1V: ");
    Serial.println(LRA1V);     //debug
  }

  LRA2V = map(POT1V, 1000, 100, 0, 255);  //convert the POT value into LRA intensity
  //LRA2V = constrain(LRA2V, 0, 255);
  if((DEBUG == TRUE)||((REPORT == TRUE)&&(counter1 == 0))){
    Serial.print("LRA2V: ");
    Serial.println(LRA2V);     //debug
  }

  LRA3V = map(POT1V, 1000, 100, 0, 255);  //convert the POT value into LRA intensity
  //LRA3V = constrain(LRA3V, 0, 255);
  if((DEBUG == TRUE)||((REPORT == TRUE)&&(counter1 == 0))){
    Serial.print("LRA3V: ");
    Serial.println(LRA3V);     //debug
  }
```

```
  LRA4V = map(POT1V, 1000, 100, 0, 255);  //convert the POT value into LRA intensity
  //LRA4V = constrain(LRA3V, 0, 255);
  if((DEBUG == TRUE)||((REPORT == TRUE)&&(counter1 == 0))){
    Serial.print("LRA4V: ");
    Serial.println(LRA4V);      //debug
  }
  */
//Constrain LRA intensity levels
  LRA1C = constrain(LRA1V, 0, 255);
  LRA2C = constrain(LRA2V, 0, 255);
  LRA3C = constrain(LRA3V, 0, 255);


//Activate LRAs
  analogWrite(LRA1, LRA1C);   //LRA will vibrate with PWM value between 0-255 depending on POT
voltage value
  analogWrite(LRA2, LRA2C);   //LRA will vibrate with PWM value between 0-255 depending on POT
voltage value
  analogWrite(LRA3, LRA3C);   //LRA will vibrate with PWM value between 0-255 depending on POT
voltage value


//FORCE SENSOR RESISTOR (FSR) CODE:
//Read the sensor value
  FSRV = analogRead(FSR);  //FSRV yields values from 0-650.
  FSRV1 = map(FSRV, 0, 550, 40, 255);  //20, 120
  FSRV1 = constrain(FSRV1, 40, 255);
  analogWrite(LRA4, FSRV1);
  if((DEBUG == TRUE)||((REPORT == TRUE)&&(counter1 == 0))){
    Serial.print("FSRV: ");
    Serial.println(FSRV);      //debug FSRV
    Serial.print("PTLVLV: ");
    Serial.println(PTLVLV);
    Serial.println();
  }

} //end loop
```