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Human-centered Electric Prosthetic (HELP) Hand

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DEPARTMENT OF BIOENGINEERING
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I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION
BY

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ENTITLED

Human-centered Electric Prosthetic (HELP) Hand

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE
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IN
MECHANICAL ENGINEERING
BIOENGINEERING

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Human-centered Electric Prosthetic (HELP) Hand

By

Jamie Ferris, Shiyin Lim, Michael Mehta, and Evan Misuraca

SENIOR DESIGN PROJECT REPORT

Submitted to
the Department of Mechanical Engineering
and the Department of Bioengineering

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in Partial Fulfillment of the Requirements
for the degrees of
Bachelor of Science in Mechanical Engineering
and Bachelor of Science in Bioengineering

Santa Clara, California

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Abstract

Through a partnership with Indian non-profit Bhagwan Mahaveer Viklang Sahayata Samiti, we designed a functional, robust, and and low cost electrically powered prosthetic hand that communicates with unilateral, transradial, urban Indian amputees through a biointerface. The device uses compliant tendon actuation, a small linear servo, and a wearable garment outfitted with flex sensors to produce a device that, once placed inside a prosthetic glove, is anthropomorphic in both look and feel. The prosthesis was developed such that future groups can design for manufacturing and distribution in India.

Acknowledgements

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Chapter 1: Introduction

1.1 Background & Motivation

We want to re-empower amputees to pursue the life they desire. Approximately 1 million people become amputees every year, and amputation greatly impacts what these people can do, or how they do it [1]. Because India has a high number of amputees and deficient prosthesis availability, we identified the region as a target consumer. India also contains the level of infrastructure and organized support (through Baghwan Mahaveer Viklang Sahayata Samiti, or BMVSS) necessary for our team to make an impact in the region. In the future, our experiences here could be expanded to other countries and contexts.

Our project was supported by Santa Clara University's BioInnovation and Design Laboratory, Robotics Systems Laboratory, and Frugal Innovation Hub (FIH). SCU obtained this project in partnership with India-based BMVSS, who served as our project sponsor throughout the duration of the year. Thus, BMVSS is the customer for our completed design as well as the sponsor for ongoing development at Santa Clara University. BMVSS, as a humanitarian non-profit, fits amputees all over the developing world. The organization has made it clear that its target customer for this project is very specific: Indians who have suffered an upper-body limb loss and are looking to regain functionality through a low cost prosthetic. As a result, we focused our efforts on breaking down and understanding the needs of Indian lower-arm amputees and consequently translating these requirements into a prosthetic hand design.

India acts as a large market for many product deployments due to its quantity and density of people. There are an estimated 10 million Indians living with some form of movement impairment according to their government [2]. Being able to perform basic daily activities is critical for enabling individuals to make a living [3]. India also has a high rate of amputees, as developing countries tend to have less stringent safety codes

and poorer medical care leading to more accidents and diseases resulting in limb loss [4]. These conditions make for a marketplace where a frugal prosthetic hand could benefit a large contingency of people and spur the innovation and design of more such devices.

Our goal was therefore to design an electrically powered prosthetic hand that communicates with unilateral, transradial amputees through a bioelectro-mechanical interface. We aimed to design and construct a versatile, single actuator hand that can be easily manufactured in India at a dramatic cost reduction from the current standard while maintaining performance measures near those found in other modern prostheses.

1.2 Literature Review

We began by briefly outlining the recent history of prosthetic hand research and development. This contextualizes the technologies available so that we may better understand their complexity and how they fit into the design space.

Next, and more importantly, a literature review of the currently available myoelectric prostheses was performed. We established a couple of primary domains of current prostheses in order to better distinguish the region in which we want to operate. Furthermore, by analyzing the current market for strengths and weaknesses, we came to better understand the various strengths of prostheses as well as the associated limitations. Finally, we have identified a key few factors that we find to be lacking in current prostheses that we hope to address in our design.

1.2.1 A Brief History of Prosthetic Hand Technologies

In understanding the breadth of prosthesis technologies available today, it is helpful to briefly look to the history of prosthetic hands.

The prosthetics industry progressed slowly until World War I when the magnitude of the conflict and the relatively advanced medical technology available yielded an unprecedented number of amputees. Similar increases in prosthesis demand occurred

during World War II and again during the thalidomide tragedy, effectively spurring the industry forward. In 1948, Bowden developed the first cable-driven tension-actuated prosthesis with a dual hook end attachment (see Fig. 1) [5]. This family of prostheses is still widely used today due to their speed, strength, durability, and affordability [5, 6].
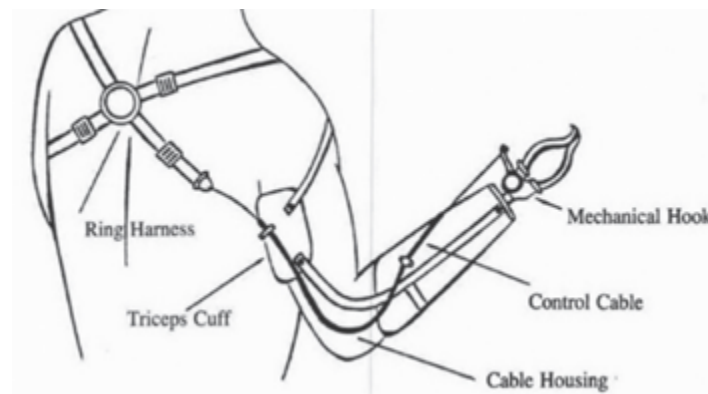
Fig. 1: Bowden's body-powered split-hook prosthesis [5].

While attempts at pneumatic, gas, and electric powered prostheses had been made since 1919, it was not until 1948 with the invention of myoelectric control that externally-powered prostheses were practical [5]. In electromyography, or EMG, surface electrodes applied to antagonistic muscles are used to detect changes in electrical potential generated by nerve activity [7]. Because muscle contraction and relaxation are governed by action potentials in motor neurons, the changes in electrical potential collected by the surface electrodes directly relate to muscle contraction and relaxation. In amputees, reading nerve activity allows technology to approximate what the amputee is trying to do in their phantom limb.

However, EMG received little attention until Russian scientist Alexander Kobrinski designed the first complete myoelectric prosthetic arm in 1960. Over the next 20 years, the weight, speed, strength, and durability of myoelectric prostheses were improved, and by the 1980s, myoelectric prostheses were commonly used [5]. Myoelectric control offers improved senses of bodily restoration and comfort that most body powered prostheses lack. However, they rely on battery power, and depending upon the

complexity of the device, users can require increased training with the device [3, 5, 6, 8, 9,10].

Current research in hand prostheses is divided into two primary camps: Many cutting edge research facilities such as the Johns Hopkins Applied Physics Laboratory are dedicated to developing cutting edge technologies including targeted muscle reinnervation, myoelectric control, and exoskeletal prostheses [8, 11]. Other researchers are applying existing technologies and creating low-cost, high-functioning prostheses. These designs are primarily human-centered, emphasizing the balance between user acceptance and cost.

For the most part, researchers on both sides recognize the advantages of anthropomorphic design. Anthropomorphic prosthetic hands are not only more aesthetically pleasing than hook styles, they generally improve functionality as they best model human function. They are perfectly suited for ordinary daily tasks and adapt quickly to "dynamic unstructured environments" [7]. Users find them more intuitive to use, and they provide an increased sense of bodily restoration. Most importantly, they improve the aesthetic design of the prosthesis as they can be fitted into a human looking glove.

Many research groups also opt for myoelectric control due to the low associated rejection rates[1] [12]. Electric prostheses experience rejection rates of 17 to 41% while body-powered hands are rejected 65 to 80% of the time and body-powered hooks are rejected 32 to 51% of the time [6]. This is primarily explained by the limitations of body-powered prostheses; due to mechanical inefficiencies, body-powered prosthetic hands require a high activation force in order to deliver a relatively small pitch force. They also offer limited degrees of freedom and are restricted to rigid finger design. In combination

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[1] There are, however, a few research groups currently developing improved body-powered prostheses. For example, a team at Delft University recently published research on a lightweight, hydraulic, body-powered prosthetic hand possible of achieving grasping metrics similar to those achieved in myoelectric control but with increased proprioceptive feedback [3].

with weight, these design limitations hinder the functionality and comfort of body-powered prostheses [6].

Myoelectric control presents its own challenges, however. The level of detail that can be read through EMG is limited, and the best myoelectric control systems currently available are complex and expensive [7]. Additionally, the interface between the electrodes and the skin must be clean in order to receive the clearest possible EMG signal; the signals are easily obscured by even every-day sweat and dirt.

An alternative option to EMG prosthetic control is the use of mechanomyography to produce an input signal. Mechanomyography, or MMG, also collects data on muscle contraction and relaxation, using physical sensors instead of electrodes. In general, there are three established types of MMGs: acoustic myography (AMG), vibromyography (VMG), and phonomyography (PMG). AMG utilizes a combination of microphones, accelerometers, and piezoelectric contact sensors to measure the sound of the muscle contraction, which increases as contraction force increases. AMG has been documented for use in prosthetic control, as well as in research settings for measuring muscle fatigue or function [13]. VMG, on the other hand, measures the vibrations associated with muscle contraction or relaxation, often using contact sensors or microphones. VMG can also be referred to as acceleromyography. Lastly, PMG is similar to AMG in that it measures low frequency sounds associated with muscle contraction. PMG is most typically used in a research setting to study muscle function, whereas AMG and VMG have been documented for use in prosthetic control [13].

Overall, mechanomyography describes the use of sensor combinations to quantify muscle activity. The major benefit of MMGs over EMGs for prosthetic control is that MMGs are less susceptible to physiological interference than EMGs [13]. This is most beneficial in that it removes the major concern of maintaining reliable and precise contact with the skin, which could be disrupted by dead skin, sweat, or other physiological changes when used with EMGs. The use of MMGs for prosthetic control is

a more recent application than the use of EMGs for prosthetic control, and is less documented.

Within these regions of research, there are a number of central research topics that appear consistently. The issue currently dominating design is the method of mechanical finger control. While some prostheses embed many motors throughout the hand in order to individually control every joint, the number of motors required to do so either significantly increases the size and weight of the prosthesis or requires many high-end and expensive motors. Therefore, most low-cost prostheses utilize under-actuation to enact passive-adaptive control in anthropomorphic hands using only one or two motors [3, 6, 14, 15, 16]. Under-actuation can be achieved through a number of mechanisms, two of which are tension and slip block actuation.

Tension Actuation: These systems rely on cables run through the fingers such that when the cable is pulled, the finger curls in a progression similar to when a human hand forms a fist. When grasping an object, each segment will stop as it comes into contact with the object, but the rest of the segments will continue curling. This will continue until all segments are either in contact or fully bent. This customized shaping is possible because of the even tension distribution along the finger as compared to the constraining of angle relationships between segments of the finger [3, 9, 15, 16].
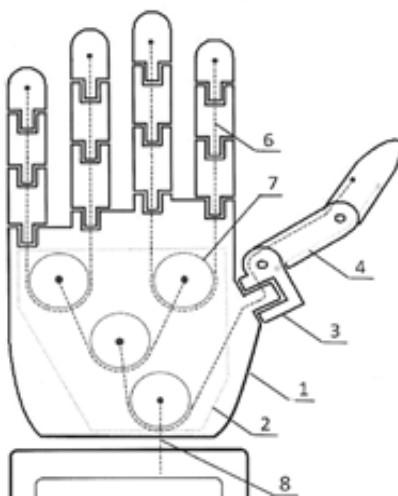
Fig. 2: Pulley based tendon actuation system [15].

In order to control all fingers with a single motor, the tension in each finger must be linked. A variety of linkages have been used in modern prostheses, among them longitudinal lever carriages and pulley chains. Lever carriages apply tension first to the thumb and then progressively transfer the tension to the latter fingers by sliding along a longitudinally extending guide as the bending in each finger halts. The carriage movement calibration can be complex, but there is also a great amount of adaptability and specialization. For example, a pin connection can be used to restrict the carriage's sliding and yield a pinching motion [3].

Pulley chains provide an alternative tension actuation mechanism. A series of free-sliding pulleys like that shown in Fig. 2 allows for tension to be transferred to the most easily bent fingers. The fingers therefore bend to fit the grasped object in a manner similar to the lever carriage design. This design requires less mechanical and calibration precision but offers less opportunity for specialization [15].

Slip Block Actuation: This system relies on the transfer of torque along finger members as they come into contact with an object. The transfer occurs when a slip block is compressed by the object, effectively causing the next member to rotate because the previous no longer can (see Fig. 3). The slip block mechanism provides high passive adaptation while maintaining both a low weight and a small profile [16]. It also escapes many of the complications present in the use of tension cables, namely the lack of mechanical advantage or torque, the wear incurred by sliding cables, and the interdependence of all fingers.
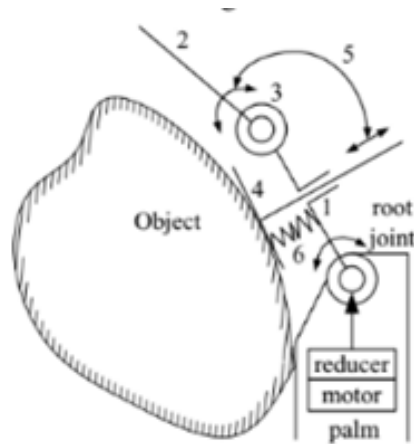
Fig. 3: Slip block actuation system [16].

Beyond the mechanical basics, a number of additional functions have been recently developed which enhance the anthropomorphism of the prosthesis.

Material Selection: Material selection is crucial to the design of a lightweight yet strong prosthesis. Most material selection criteria are not unique to our project and as such will not be emphasized here, but the incorporation of 3D printed materials requires special consideration. 3D printing is a customizable, cheap, fast, accessible way to create unique parts with complex geometries, making it useful in low-cost prosthesis design. However, the strength properties of 3D printed materials vary greatly by printer type, printer settings, and material type. Some 3D printed materials can in fact achieve great enough density and strength to be adequate for high quality prostheses, but many fall short [17]. 3D printed parts should therefore be designed carefully and tested comprehensively before use.

Thumb Swivels: Most low-cost prosthetic hands now include a thumb swivel mechanism. The swivel generally must be operated by a human hand, limiting its optimal use to single amputees, but the use of a simple button or lever to activate thumb angle alteration allows for a minimally opposable thumb while requiring very little additional mechanics [3, 6, 15, 18].

Torsional Springs: Many prostheses now also include torsional springs in the finger joints in order to define the resting position while maintaining a low spring profile. These springs can also be selected to achieve precise and varying tension in each finger joint [3, 7, 14].

Force Magnification: Various force magnification mechanisms have been developed in the pursuit of human grip strength. A research group at the Tokyo Institute of Technology recently published on a two stage force application mechanism wherein broad movements are performed under flexion drive and grip application is achieved via a force magnification drive (see Fig. 4). By combining the two mechanisms, both high grip force (20 N) and fast grip speed (0.47 s), two metrics that are typically diametrically opposed, were achieved together [14].
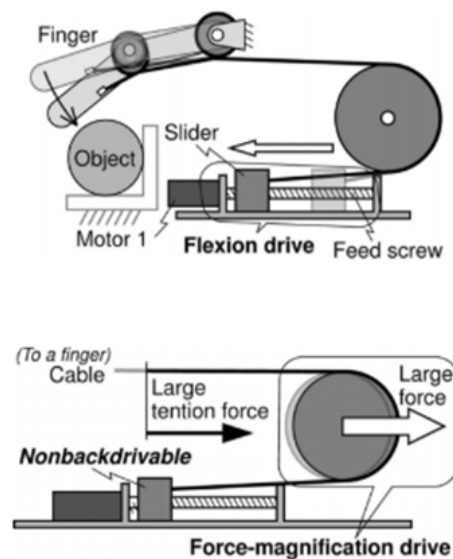
Fig. 4: Two stage force application [14].

Embedded Sensors: The use of sensors along the finger has recently increased in popularity. Simple flexure sensors can be used to recognize contact, or more complex sensors can be used to recognize slippage and contact shape. This data can be used to automate grasping of the hand as the force application can be modulated to automatically maintain a firm but gentle grip customized to the object [18,19]. Contact recognition can also be used to deliver vibrotactile feedback to the user. By having the

prosthesis vibrate slightly upon contact, the user can detect grasping without visual identification [7, 18, 19].

These technologies each have the own strengths and weaknesses, and different engineering groups employ different combinations thereof. The prosthesis engineering community remains undecided on how best to integrate existing technologies. However, in a dissertation Severin Tenim attempted to categorize and contrast some of the primary components of the prosthetic hand. Fig. 5 and 6 analyze various finger and palmar mechanism designs.
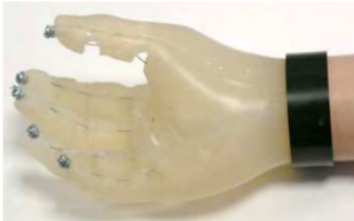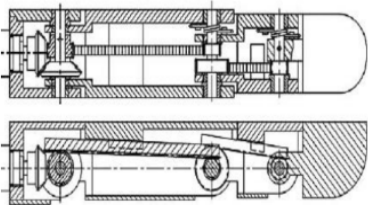
	Concept 1: Linkage-driven actuation	Concept 2: Tendon actuation	Concept 3: Geared actuation
Advantages	• Mechanically sound • Accurate control of closing trajectory • Reliable • Relatively inexpensive • Able to amplify input force through mechanical advantage	• Lightweight • Inexpensive • Fewer moving parts • Easily conforms to varying geometries • Mimics anatomical tendon mechanism • Ease of assembly and production • Simple and compact	• Constant torque throughout closing range • Rapid closing speeds • Precise control of individual digits possible • Adjustable closing trajectories using control system
Disadvantages	• Many moving parts • Limited conformability to varying geometries • Challenging assembly	• Wear due to actuating tendon • Dislocation of actuating wire from routing pulleys • Individual control of digits challenging	• Requires rotary actuation (i.e. motor) and control system • Difficulty machining due to small components • Complex assembly • Heavy and noisy • Expensive

Fig. 5: Advantages and disadvantages of underactuated finger mechanism designs [3].
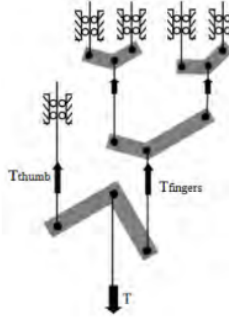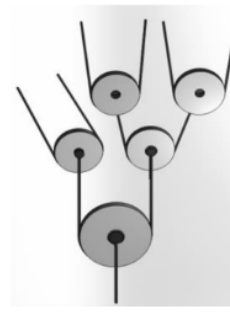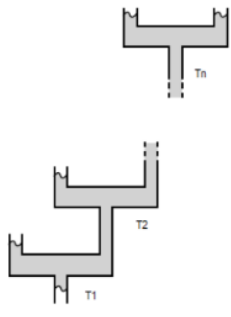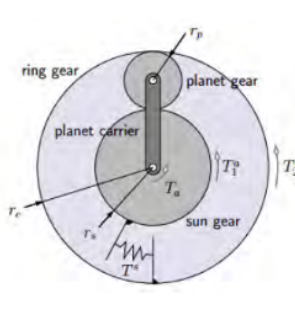
	Concept 1: Differential Levers (Seesaws)	Concept 2: Moveable Pulleys	Concept 3: Fluidic T-pipes	Concept 4: Planetary Gearing
Advantages	▪ Easily adjusted lever arm length, enabling uneven force distribution between fingers ▪ Pivoting levers allow relative motion between fingers ▪ Ease of manufacture ▪ Design simplicity	▪ Low resistance and friction ▪ Simple design ▪ Easy system analysis ▪ Relative motion allowed between fingers	▪ Uneven force distribution between fingers possible ▪ Low space requirements ▪ Design simplicity ▪ Efficient force transmission when using incompressible fluid	▪ Constant force transmission independent of position ▪ Mechanically reliable ▪ Large transmission ratios
Disadvantages	▪ Large operating space requirement ▪ Risk of dislocation of the actuating wires ▪ Low efficiency when in guided-slots	▪ Derailment of actuating wires when tension released ▪ Uneven adjustment of lever arm not possible ▪ Low efficiency when in guided-slots	▪ Requires a fluid reservoir ▪ Increased weight due to fluid ▪ Pumping/pressurising mechanism required ▪ Risk of leakage ▪ Adjustment of forces requires new piping/flow-nozzles	▪ Expensive ▪ Difficulty in manufacture and assembly ▪ Complex design ▪ Noisy transmission ▪ Fixed gear-ratios ▪ Needs rotary force input

Fig. 6: Advantages and disadvantages of differential palmar mechanism designs [3].

1.2.2 Literature Review of Currently Existing Prosthetic Hands

Primary to the literature review was a thorough identification and analysis of current myoelectric prostheses. Tables 1 and 2 summarize the specifics of the identified prostheses. Fig. 7 through 14 depict a few of the hands analyzed (those that are further compared in Fig. 15-17).

Table 1: Myoelectric prosthetic hand literature review summary data [20 - 41]

Product/Paper Name	Type	Cost	Myo vs Body Powered	Material	No. of Joints	Control Scheme	Weight
Deka (Luke) Arm	Commercial	$100,000	Compatible with many different control sensors including EMG	Metal and Ploymer	15	Proportional Speed Control	1.05-1.14 lbs
iLimb Quantum	Commercial	$80,000	Myoelectric	Titanium, Industrial Plastic, and Metal	11	Gesture, App, Muscle and Proximity 24 control programs	
Modular Prosthetic Limb (MPL)	Research		Myoelectric, TMR	Metal	19	Closed loop control	
Ottoboch Michaelangelo	Commercial	$60,000	Myoelectric	Industrial Plastics	6	Proportional Speed Control	0.93 lbs
Southampton Remedi-Hand	Research		Myoelectric	Carbon-Fiber Epoxy Composite and Thermoplastic	14	SAMS	0.88 lbs
Ottoboch Bebionic 3	Commercial		Myoelectric	Industrial Plastics	11	Proportional Speed Control Proportional Force Control	1.32 lbs
High-Performance Anthropomorphic Robot Hand with Grasping-Force-Magnification Mechanism	Research		Neither		14		0.72 lbs
The Taska	Commercial	$35,000	Myoelectric	Industrial Plastics	9		
Ottoboch SensorHand Speed Myohand Variplus Speed	Commercial		Myoelectric	Metal	3	Proportional Speed Control Proportional Force Control 6 control programs	1.01 lbs
Vincent GmbH Evolution 3	Commercial		Myoelectric			Single Trigger Control 14 programmed grips	0.851 lbs
Vanderbilt Multigrasp Prosthetic Hand	Research		Myoelectric	ABS Plastic	9	Multigrasp Myoelectric Control	1.20 lbs
Openbionics Hero Arm	Commercial	$2,000	Myoelectric	3D Printed	11		<2.2 lbs
WO2016005871A1	Patent		Body Powered	Metal and Polymer	15		0.52 lbs
YouBionic	Commercial	$1,747	Myoelectric	3D Printed	15	Arduino IDE compatible; self-programmed	
Dextrus	Open Source	$1,100	Myoelectric	3D Printed	14		1 lb
Becker Imperial Hand	Commercial	$650	Body Powered	Annealed Steel	10		0.91 lbs
Tact	Open Source	$250	Myoelectric	3D Printed	11	Arduino; self-programmed	0.77 lbs
Exiii Hackberry	Open Source	$200	Infrared Sensing of Contraction	3D Printed	14	Arduino Micro	1.43 lbs
RoboHand	Open Source	$150	Body Powered	3D Printed	14		
Raptor Reloaded (e-Nable)	Open Source	$50	Body Powered	3D Printed	6	-	
Cyborg Beast	Open Source	$50	Body Powered	3D Printed	6	-	
Shadow Dexterous Hand E Series	Commercial		Myoelectric	Metal and Polymer	24	Position Control Compatible with ROS, PID	

Table 2: Myoelectric prosthetic hand literature review summary data (cont'd)

Product/Paper Name	Anthropo morphism (1 to 5)	Number of Actuators	Maximum Grip Force (N)	Grip Speed	Active Grip?	Add-Ons
Deka (Luke) Arm	4	4			No	Vibrotactile feedback, 1.4 kg
iLimb Quantum	5	6	136	0.8s	Yes	
Modular Prosthetic Limb (MPL)	4	10			Yes	Lots of sensors…
Ottobock Michaelangelo	5	2	70	0.37s	No	
Southampton Remedi-Hand	3	6	38	0.84 s	Yes	Pressure and slip sensors
Ottobock Bebionic 3	5	5	140.1	0.9 s (power grasp), 0.4 s (tripod grasp), 0.9 s (key grasp)	Yes	Manually Adjustable Thumb, vibration or audible beep feedback
High-Performance Anthropomorphic Robot Hand with Grasping-Force-Magnification Mechanism	3	6	100	0.47 s to close, 1 s to full grip strength	No	Flexion and force application drives
The Taska	4	6			No	Motorized thumb control
Ottobock SensorHand Speed	2	1	100	300mm/s	Yes	SUVA Thumb
Myohand Variplus Speed	5	6			Yes	Grip Sensing strain gauge between thumb and index finger
Vincent GmbH Evolution 3	4	6	60	0.8 s (2)	Yes	Vibration
Vanderbilt Multigrasp Prosthetic Hand	4	4	45		No	Automated opposition/reposition of thumb
Openbionics Hero Arm	4	5			No	
WO2016005871A1	4	1			No	Tension Actuated
YouBionic	1	6			No	
Dextrus	2	6			Yes	
Becker Imperial Hand	2	1	30		No	
Tact	2	6	16	250 deg/s	No	
Exiii Hackberry	3	3			No	
RoboHand	2	1			No	
Raptor Reloaded (e-Nable)	2				No	
Cyborg Beast	2				No	
Shadow Dexterous Hand E Series	2	20			Optional	Pressure sensors, can have pressure/microslip/temp etc

Fig. 7: The I-Limb Quantum [42]
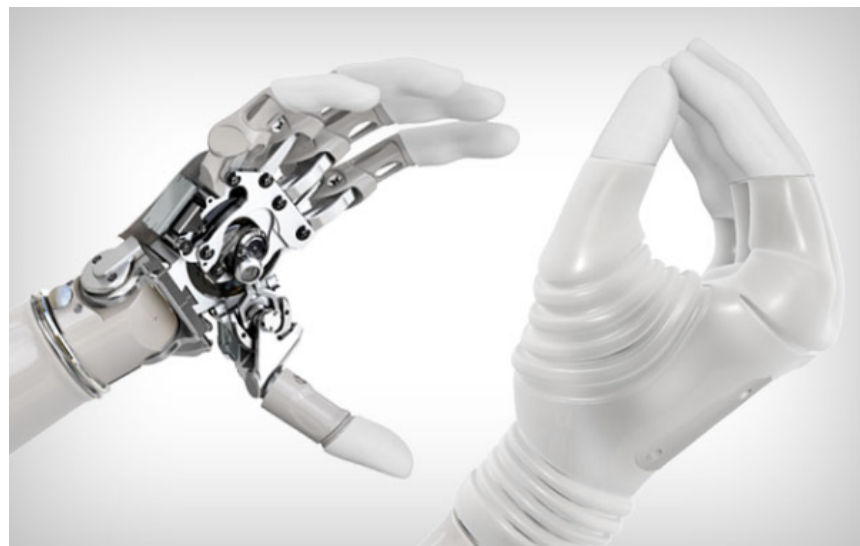
Fig. 8: The Ottobock Michelangelo [43]

Fig. 9: The Taska [44]

Fig. 10: The Ottobock SensorHand MyoHand VariPlus Speed [45]

Fig. 11: The OpenBionics Hero Arm [46]

Fig. 12: The Dextrus [47]
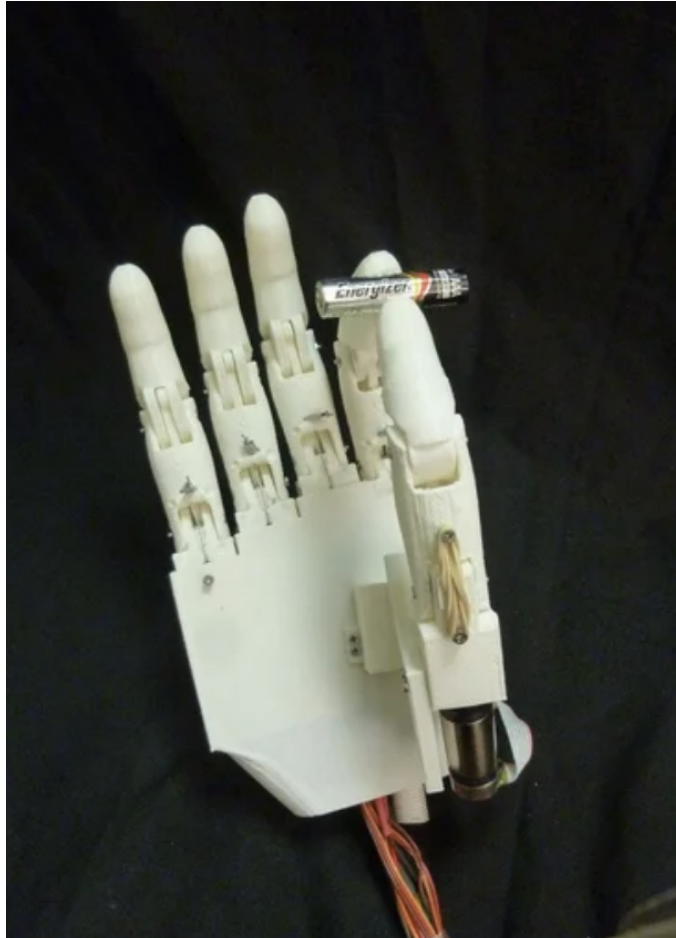
Fig. 13: The Tact [32]

Fig. 14: The Exiii HackBerry [48]

These prostheses have been classified into two groups based on cost; nearly all of the prostheses cost less than $2,000 or more than $35,000. Radar plots were therefore constructed comparing a small, representative selection within each category (see Fig. 15 and 16). Furthermore, a radar plot comparing two 'high cost' and two 'low cost' prostheses was constructed in order to highlight the relationships between the two categories (Fig. 17).

A small selection of comparison criteria were selected based on the critical factors in prosthesis rejection and the distinguishing factors between prostheses. All axes have been normalized to be represented on a scale of zero to one, and the maximum number (or multiplication factor) can be found next to the axis label. Anthropomorphism was qualitatively assigned a score from one to five with five being the most anthropomorphic. Active grip functionality has been assigned a binary value of 1 or 0.5 with 1 representing active grip and 0.5 representing the lack thereof.
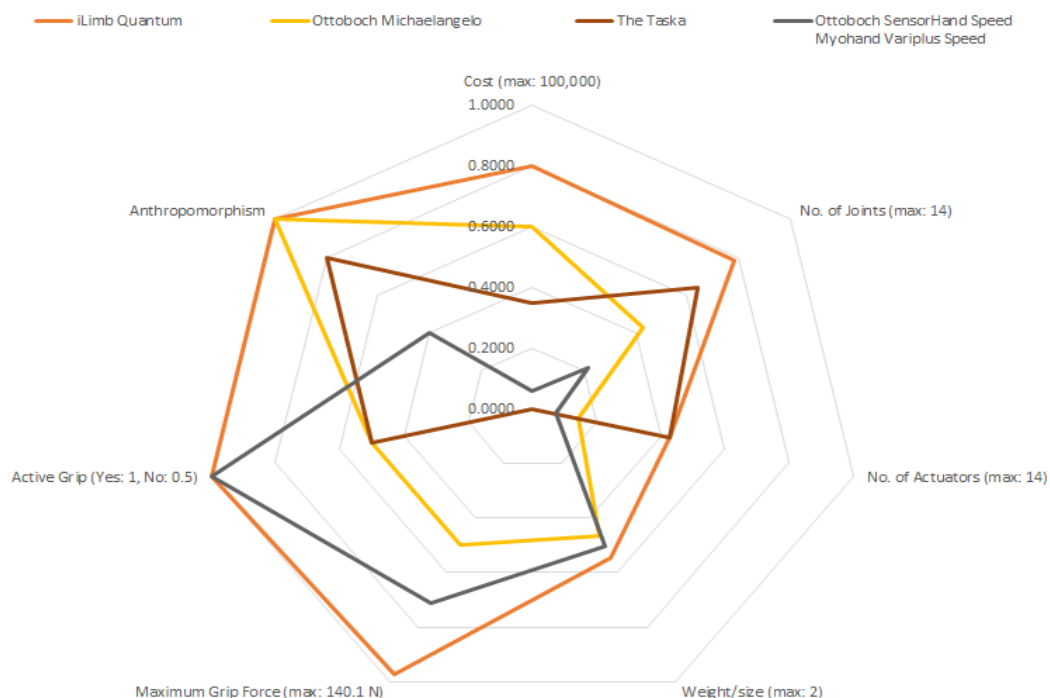
Fig. 15: Comparison of high cost myoelectric prostheses

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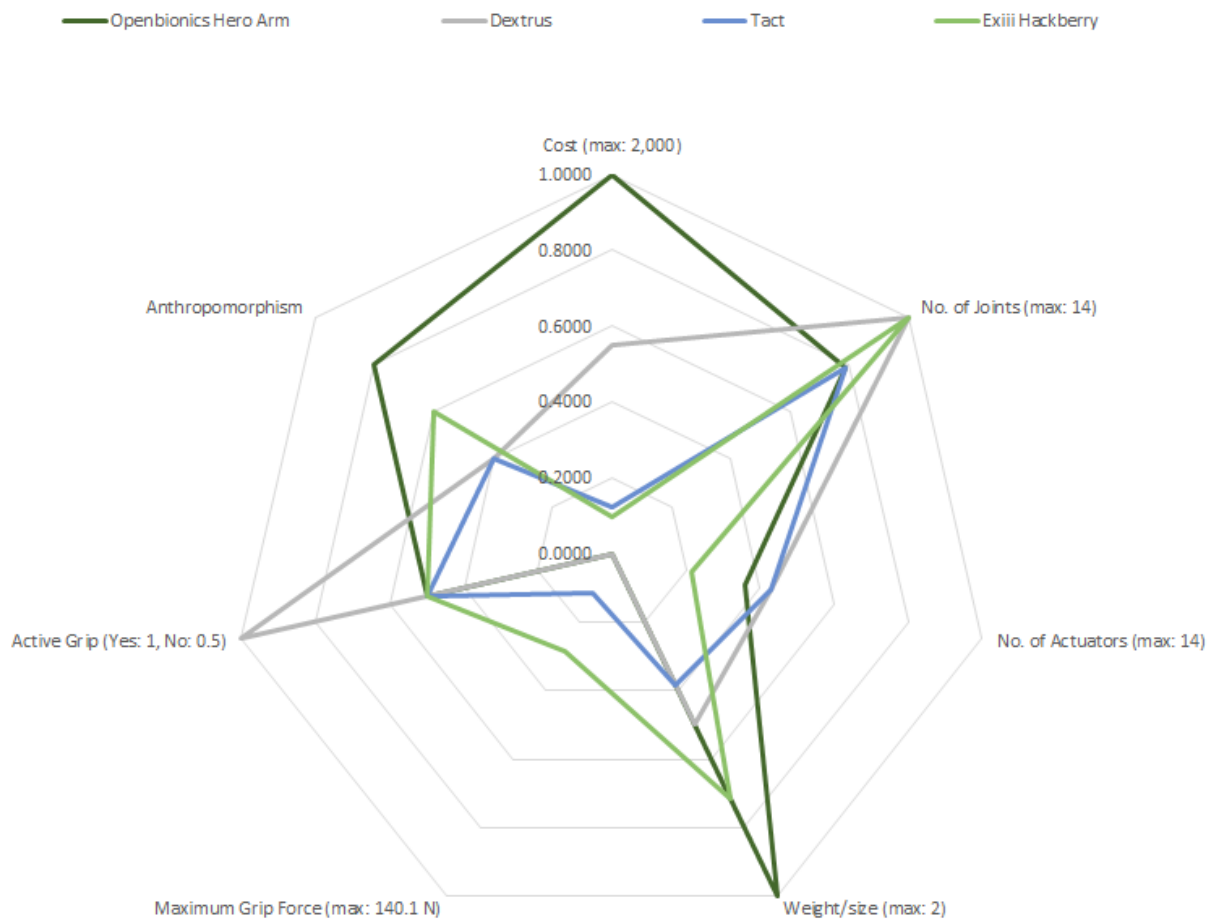
Fig. 16: Comparison of low cost myoelectric prostheses
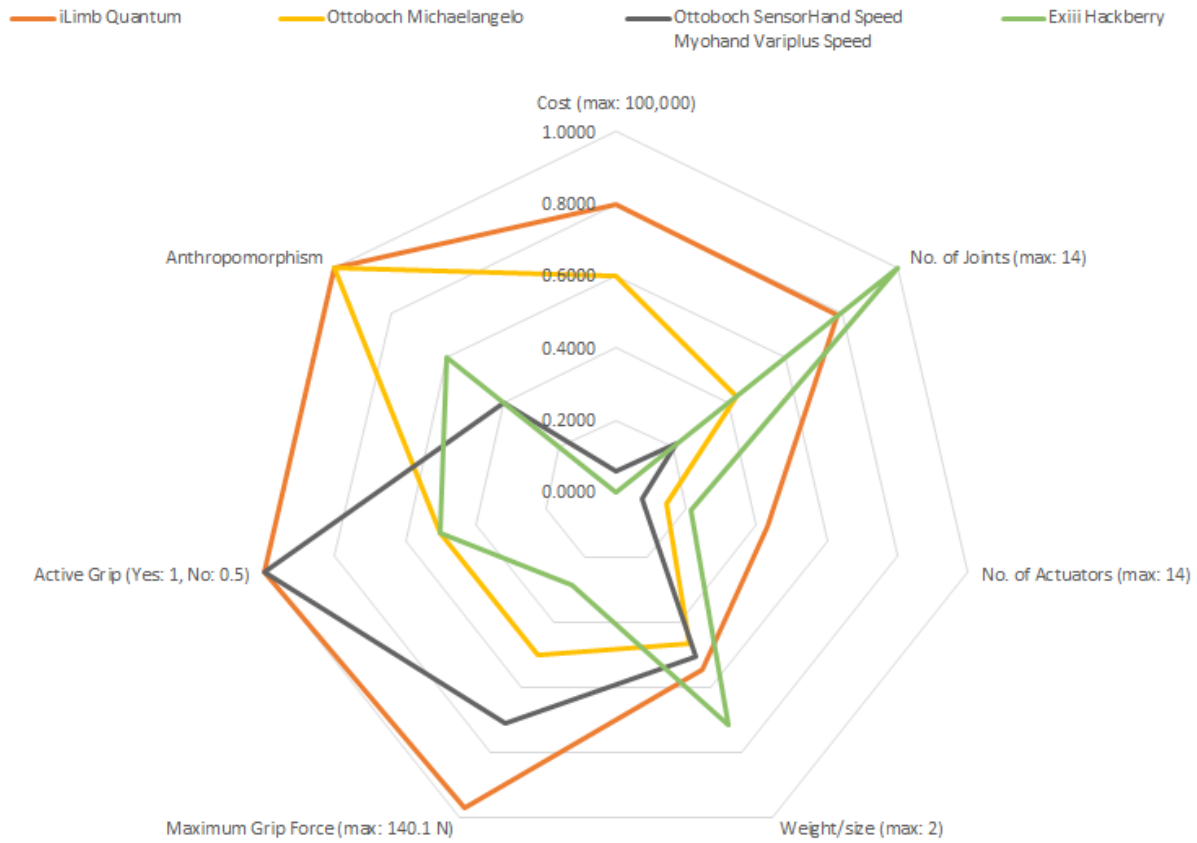
Fig. 17: Comparison of high and low cost myoelectric prostheses

1.2.3 Improvement Analysis

From the comparison of low and high cost myoelectric prostheses, multiple trends were identified:

1. The high cost prostheses tend to outperform the low cost prostheses on most metrics, but they do not necessarily contain more actuators.
2. High cost prostheses are much more likely than low cost prostheses to include active (or closed loop) control.
3. High cost prostheses tend to weigh less than low cost prostheses.
4. High cost prostheses tend to use more durable materials than low cost prostheses, many of which are 3D printed.

5. The number of degrees of freedom and actuators vary wildly even within the high end prostheses depending on the target user base.

These trends were used to inform our design process by orienting us towards the importance of weight, cost, active control, grip force, and anthropomorphism. The analysis also highlighted the lack of importance of the number of actuators and number of joints. These statistics should be allowed to follow from the functional design rather than pursued in and of themselves. Furthermore, allowing a reduction in the number of actuators and number of joints aids in the reduction of weight and cost as well as in the increase of grip force due to simplifications of the mechanical system.

Ultimately, while the technology around prostheses has developed dramatically, a disconnect exists between existing needs and the prosthetics research currently being done. By re-orienting towards human-centered design, were better be able to decide between existing technologies. Cost was also better balanced with functionality as we removed features undesired by the Indian user case.

An Italian research group recently published on user performance and compliance in anthropomorphic myoelectric prosthetic hands of varying complexity. By applying three different control mechanisms to a high-end, 16 degree of freedom prosthesis, they were able to test functionality of the prosthesis under varying levels of passive and active actuation, varying complexity of myoelectric control, and modulation of vibrotactile feedback. As seen in Fig. 18, a moderately simple control mechanism was preferred by users due to the increased attention required by prostheses of increased complexity. Additionally, vibrotactile feedback was well received. Overall, the complexity of the prosthesis had little bearing on the grip functionality, indicating that once minimal functionality is achieved, user acceptance ought to be the primary factor in prosthesis design [49].
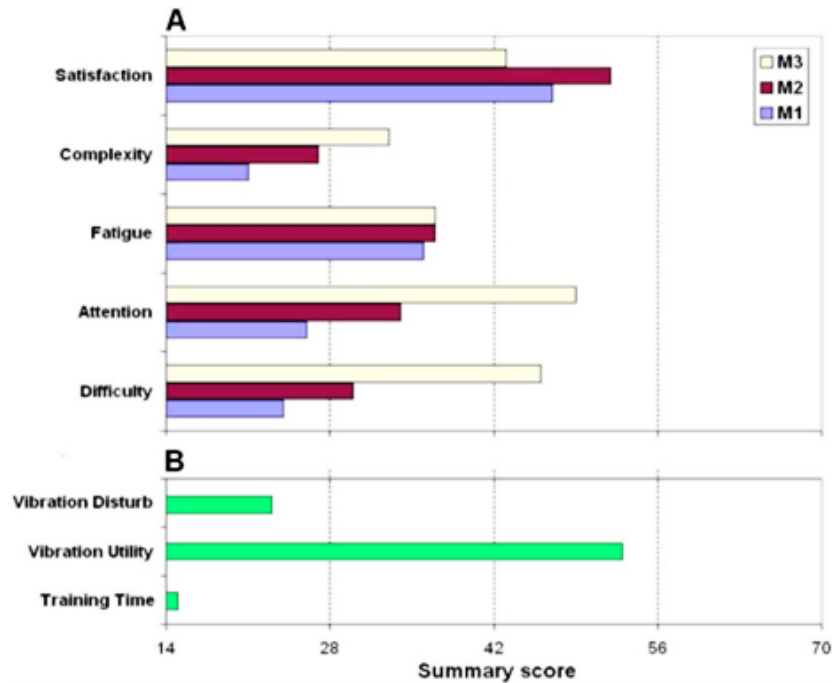
Fig. 18: (A) Subjective comparison between control mechanisms and (B) summary of vibrotactile feedback impact [49].

An excellent example of such human-centered design is in the development of the Jaipur foot, the lower leg prosthesis used by India based prosthesis nonprofit Bhagwan Mahaveer Viklang Sahayata Samiti, or BMVSS. In their design of the Jaipur foot, they emphasized the needs of their specific client base, prioritizing use of the prosthesis without a shoe and ability to crouch on the prosthesis in addition to traditional concerns of durability, cost, and manufacturability [21]. They have achieved tremendous success with this prosthesis and have grown to be the largest prosthetics company in the world, fitting over 20,000 Jaipur feet a year in India alone.

1.2.4 Market Analysis

We partnered with BMVSS to create a low-cost electric prosthetic hand to be used in India alongside the Jaipur foot. BMVSS supplies free prostheses to those in need, so the target consumer was in India's lower class. The majority of Indians live on less than a dollar a day income, and most amputees are unemployed or work in poor agricultural

settings after their amputation [50]. The prosthetic hand was therefore designed as to be cheap enough that BMVSS can continue to provide the prostheses for free.

In our design, we pursued maximization of functionality (weight, cost, active control, and grip speed and force) within a low-cost device. Furthermore, the aesthetic component was given priority as it is paramount to prosthesis acceptance in India. The perception of amputees in India leads amputees to hide their amputation even at the cost of functionality; many wear purely cosmetic prostheses. We therefore ultimately balanced between cost, function, and aesthetic in the design of a frugal electric prosthetic hand for use this this particular Indian context.

1.3 Project Goal

The goal of this project was to design an electrically powered prosthetic hand that communicates with unilateral, transradial amputees through a bioelectro-mechanical interface. We designed and constructed a tendon-actuated, versatile, single actuator hand that can be easily manufactured in India at a dramatic cost reduction from the current standard while maintaining performance measures near those found in other modern prostheses. Finally, we carefully documented and organized the project such that future work could be done to iteratively test and improve as well as to develop a manufacturing process for the device.

Chapter 2: Team and Project Management

This senior design team was an interdisciplinary collaboration between Mechanical Engineering and Bioengineering. It was composed of four undergraduate engineering students, three of which are mechanical engineering students. The undergraduate team was supported by an auxiliary team of graduate students, led by John Paul Norman, as well as advisors from both mechanical and bioengineering. Furthermore, a partnership with students from the Public Health department was established in the early stages of the project to aid with background research and qualitative support.

2.1 Project Challenges

The interdisciplinary aspect of this project, as well as the complexity of the engineering design, posed project challenges in communication and integration. Further challenges were introduced in the context of an international partner, as working with an Indian partner created unique cultural and communication challenges. To mitigate some of these potential risks, the team created Table 3 to address concerns.

Table 3: Potential project management challenges and resolutions

Potential Challenge / Risk	Resolution
New customer needs introduced from BMVSS	Adapt prototype and incorporate need if realistic. Establish importance of meeting senior design project deliverables if necessary.
Critical feedback to design decision from BMVSS	Document how design decisions were fueled from BMVSS input.
Unexpected leave of a team member due to a personal matter or illness	Potentially adjust project scope. Keep all team members informed of all subsystems throughout process so they can take over when needed
Difficulty obtaining user testing permissions	Begin early and establish a backup plan if initial user testing sources fall through
Component failure	Order spare materials and parts ahead of

	time such that components can be replaced in a timely matter.
Design does not function as intended	Keep advisors highly in the loop. Constantly receive feedback on engineering design to identify potential concerns early.
Overall timeline falls behind and project cannot be completed	Follow Gantt chart strictly. If project falls behind, assess situation with advisors and adjust scope if necessary.

2.2 Budget

Funding for this project was provided by BMVSS, the Santa Clara University School of Engineering, Xilinx and the Robotics Systems Laboratory. Over $4,600 was offered from a combination of these sources as summarized in Table 4.

Table 4: Senior design project funding

Source	Amount
BMVSS	$1500.00
SCU School of Engineering Undergraduate Programs	$2000.00
Xilinix	$1,100.00
Robotics Systems Laboratory Discretionary Funding	Undefined
Total	$4,600.00+

Based on funding from sources listed, there were no major budgetary concerns for this project. The only source of funding utilized was funding from SCU School of Engineering Undergraduate Programs.

2.3 Timeline

To ensure the completion of the project by Senior Design Conference, the design team followed the following timeline shown in Fig. 19.

Fall Quarter	Winter Quarter	Spring Quarter
Data Collection → Information gathering → Customer empathy → Product specs **General Design Decisions** → Grip types → Actuation mechanism → Power supply → Biointerface	**First Full & Expansive Prototype** → Mechanical design → Part selection → Order parts → Engage in customary empathy to fuel design decisions **Final Drawings for Spring Deliverable**	**Fabrication of Full Hand** → Implementation of wearable, non-invasive interface → Implementation of electrical interface → Weight of average hand → Fits in prosthetic glove → Parts cost < $400 → Fatigue and user tested **Completion of Thesis**

Fig. 19: Simplified full year design timeline (2018-2019)

2.4 Design Process

The design process for this team centered around the cycle of iteration, analysis, and redesign. The hand went through many different iterations before arriving at its final design, while each subsystem went through its own set of iterations between hand iterations. Subsystems were delegated to team members, and responsibilities were outlined in Table 5

Table 5: Subsystem division of labor by team member

Team Member	Subsystem
Jamie Ferris	Actuation, Fingers and Thumb
Michael Mehta	Actuation, Electronics
Evan Misuraca	Actuation, Palm
Shiyin Lim	Biointerface

The beginning of this design process included doing background research, understanding relevant existing technologies and defining needs and specifications. After using customer needs analysis and understanding the relevant criteria for assessing the design, initial concepts were generated. This put the project in a place where concept selection was done and decisions about individual subsystems could be made, as outlined throughout this report.

Once individual subsystems were defined, responsibilities were divided among team members. As such, each team member was responsible for one or two subsystems, and he or she completed the design, iteration, and analysis cycle for the subsystem. Once each subsystem was complete, integration and end to end prototyping occurring, which involved every team member. After initial end to end prototyping, re-design, iteration, and analysis were completed for the whole system.

2.5 Risks and Mitigations

Three main risks present to this design process were a delay in the project timeline, a lack of prototyping availability, and potential miscommunications between different teammates/subsystems.

To address potential delays in project timeline, the team continued to adjust the timeline as the year progressed, but did not budge on the final outcome of a working hand

prototype at the senior design conference. It was discussed very early on that this was a non-negotiable goal, and each member kept that in mind throughout the year.

The second potential risk to the project was a lack of prototyping materials. The design team leaned heavily on two different SCU organizations to mitigate this: the SCU Robotics System Lab and the SCU Maker Lab. The SCU Robotics System Lab provided many electrical components, such as quick connects, wires, and multimeters, while the SCU Maker Lab provided quick access to laser cutting of acrylic, 3D printing of PLA palms, and access to a sewing machine.

Lastly, the third significant risk to the project was potential miscommunications between different team members as subsystems were designed and completed in parallel. This was mitigated by team meetings twice a week, as well as constant communication through GroupMe and over Google Docs.

2.6 Team Management

This team was organized to maximize productivity and avoid conflict. Team members were assigned distinct roles for meetings and within the actual engineering project. While each team member took lead of a certain subsystem, all members were responsible for staying informed and supporting the other members since the distribution of work was uneven. The distinctiveness of roles helped split up all work (research, concept generation/selection, engineering design, fabrication, etc). Additionally, it kept all members accountable and engaged in the project.

Throughout the year, the student team met weekly with one or both advisors, depending on advisor availability. The team also met without advisors at least once a week. Most work was conducted independently by each team member, until the team began incorporating the different subsystems together. Once subsystem integration was needed, the team began working together to ensure that integration went as smoothly as possible.

In order to create a positive team environment, all team members agreed to a code of conduct which outlined basic rules to abide by (see Appendix C). Above all formal guidelines, the team emphasized open communication and discussion of issues. This helped the team ensure successful collaboration and quick conflict-resolution.

Chapter 3: Design Criteria and Requirements

BMVSS is highly connected to the needs of these prosthetic users and therefore their expertise was extensively used to ensure that our design fit the particular Indian context. The team met three times with BMVSS's technical affiliates in the Silicon Valley and three times with one of BMVSS's Indian prosthetists to help guide product requirements and understand customer needs. Contact was ongoing throughout the project and a measure for distributing field surveys in the future has been outlined in Chapter 13.

3.1 Customer Needs

3.1.1 Customer Demographic

3.1.1.1 Population of Amputees in India

For the focus of this senior design project, our target customer fell in India. As of 2016, India has an estimated population of over 1.32 billion people. As of 2018, India's GDP is the 116th largest in the world and at just 7,147 USD, their GDP per Capita is 8 times smaller than in the United States [51]. Understanding their economic limitations was critical in finding an appropriate price point for our electric prosthetic hand. According to BMVSS, the Indian government subsidizes $150 per limb on an amputee to help NGOs (like BMVSS) provide prosthetics to amputees [52]. Accessibility both in a sense of cost and fitting centers is critical to the success of our product. If future teams can produce something that can be easily manufactured and implemented into the already existing BMVSS infrastructure, cost remains as the primary concern.

Fig. 20 shows a map of BMVSS fitting centers across India compared with a population density map for the country. It should be noted that BMVSS founded its efforts in Jaipur and as a result has a much stronger location presence in Rajashtan.
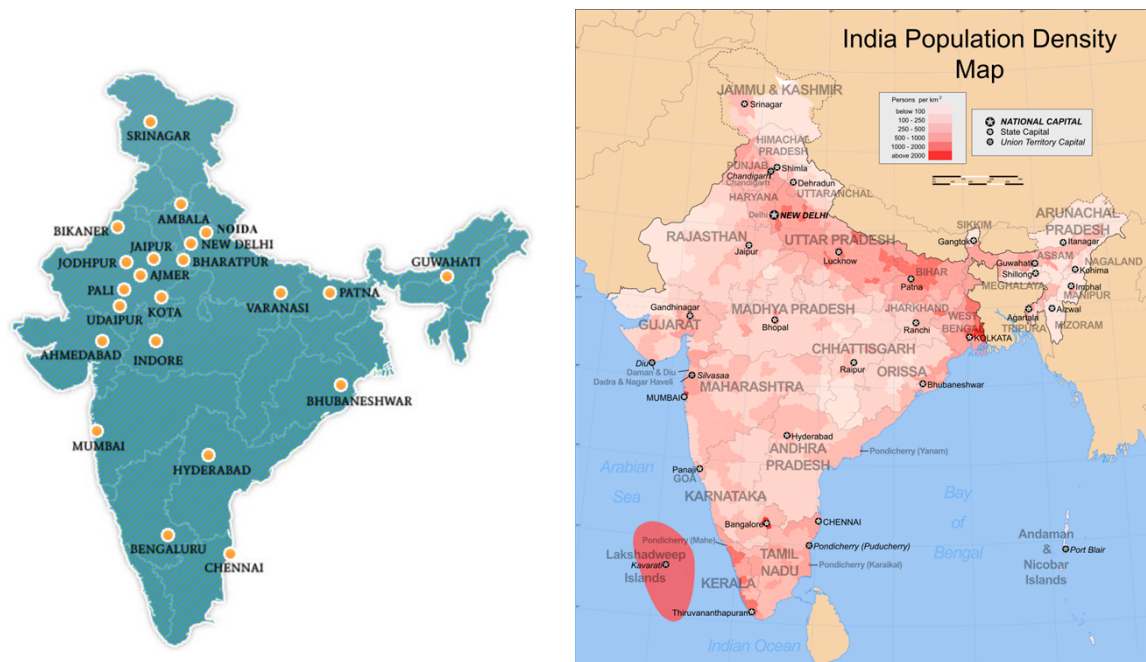
Fig. 20: BMVSS fitting centers [52] vs. Indian population density [51]

Hopefully the amount of fitting centers will continue to increase and spread evenly throughout India such that no individual is without reasonable access to a prosthetic that they need.

55.6% of India's labor force is accounted for by the service sector, 26.3% by the industrial sector and 18.1% by the agricultural sector [51]. All of these labor forces were initially kept in mind when designing the prosthetic hand. After conducting the interviews with the prosthetist, however, we narrowed in on a more white-collar urban labor force [53]. Thus those working within this category of labor may have a wide variety of daily activities and this needs to be considered. In order to better target a product, It became clear very quickly that we'd need to move forward with conducting interviews and questionnaires. Very little information existed about specific work demographics in India to the point where we could interpret and analyze the information. By establishing a framework to conduct interviews, as will be discussed in the Chapter 13, we sought to create a way to eliminate this gap in information and gain a better understanding of what we were dealing with. While we were never able to conduct these interviews, future design teams will be able to pick up where we left off and use the survey that we

created (see Chapter 13). At this point in the project process we were confident that we knew enough about the accessibility concerns with customer demographics to move forward with initial design brainstorming.

It was difficult to find estimates on the specific breakdown of arm amputations (and beyond that, the distinction between transhumeral and transradial amputees). That being said, The 2001 India Census indicates that 0.6% of the population suffers from a movement-related disability [54]. With today's population estimates that suggests about 8 million people. Breaking down further into amputees was difficult and again, we needed to rely on the information that we gathered from the continued interviews with Dr. Pooja Mokul. Once specific functionality and sets of required movements were defined, we began to streamline the project and design directly for the customer and not off of any assumptions.

3.1.1.2 HELP Hand Target Demographic

In order to analyze the various potential users of frugal prosthetic hands, we segmented and broke up the large base of prosthetic hand users by important characteristics that helped to distinguish their needs. We then identified which subsets were most relevant to the BMVSS overarching goal and begun to focus our efforts on meeting the needs of a specific clientele.

Bilateral or Unilateral. The first question in frugal prosthetic hand design must be how many prosthetic hands the amputee requires. Unilateral amputees who have one functioning arm have vastly different needs than a bilateral amputee who is much more reliant on their prosthesis.

Transhumeral or Transradial. Designing for amputees with transhumeral amputations (above the elbow) introduces a new degree of freedom in the elbow joint [55]. This adds an extra degree of difficulty to achieving a high level of anthropomorphism. BMVSS made it clear that we were to design for a transradial amputee.

Circumstance of Amputation. Trauma, Disease or Congeniality. These three categories essentially wholly encompass the ways limb loss can occur. 87% of developing world amputees lose their limb due to trauma, and 6% to disease [10]. No matter what the case is for amputation, amputees have to face a mentally and physically challenging adjustment period. It also means that in the case of unilateral amputees, the remaining hand may have a varying range of functionality depending on previous hand dominance. It may be true that a recently amputated patient will be much more dependent on a prosthetic and invested in its functionality as compared to a long-time amputee who has already become adapted to life with a single arm. Similarly, a congenital (from birth) unilateral amputee is likely going to be very accustomed to performing acts of daily living with their one hand, and may not see an immediate need for a prosthetic device.
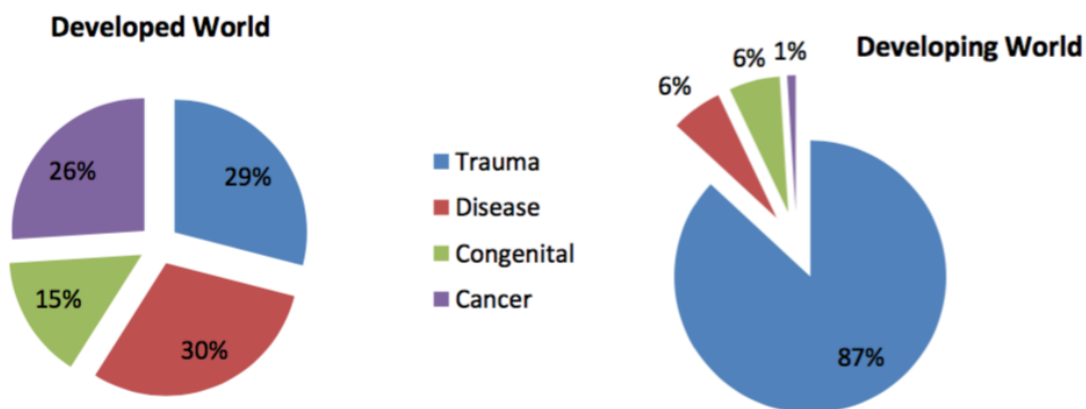
Fig. 21: Breakdown of amputee cause in the developed world vs. developing World [3]

Prosthetic Usage History. Many amputees go through numerous prosthetic hands. This may be because they wear out / break, or new improving technologies emerge [10]. It was important for us to understand the reasons that patients go through many different prostheses in order to prevent this from happening with our device. It was found to be an issue of comfort, reliability, and functionality.

Functionality. Depending upon profession, culture and lifestyle, amputees have vastly different functionality needs from their prosthetic. A blue collar amputee who has to do manual labor as a part of their daily job likely has a much greater need for a robust hand

with high grip strength. White collar amputees may have a need for more precise and gentile motion, such as typing or writing [20].

Location and Culture. The location of the user must be considered due to both manufacturing and shipping concerns. Similarly, the culture in the customer's location greatly influenced design. For example, BMVSS stresses that hook hands are consistently rejected in India due to a stigma around amputees . This made anthropomorphism a much higher priority and shifted the product focus slightly away from functionality in order to achieve a desired look [23].

Cost / Accessibility. Each amputee will need to be fitted for their prosthesis. Amputations occur at higher rates in underdeveloped countries due to less stringent safety standards and less access to high quality medical care [3]. As of 2017, 9.2 % of the world is still living on less than $1.90 per day. This makes design of a frugal electric prosthetic hand impractical as a commercial effort, and a perfect task for humanitarian Frugal Innovation funded by generous donors. In India, BMVSS has noted that $150 is given by the Indian government to humanitarian Non Governmental Organizations (NGOs) like BMVSS to fund prosthetic limbs when applicable [52]. This still falls in the range of low budget prostheses, which means some functionality must be sacrificed over high end western products. This made the prioritization of which functions are most important to a customer paramount. On top of the availability and affordability of a prosthetic hand, amputees need the ability to get to a facility where a prosthetist can equip them and train them. This requires time away from work, which can be financially devastating to a struggling worker if efficient infrastructure is not in place.

Based on the classification of needs, the following are examples of potential users of frugal, electrically powered prosthetic hands. Ultimately, one category of consumer was targeted with the design decisions:

1) Unilateral transradial amputees with blue-collar lifestyles in India.

This category of user is selected because of the feasibility of design. Transradial, unilateral amputees are far simpler to design for, and likely better fit the scope of a senior design project. Transhumeral amputations require design of an elbow joint, which if electrically powered, could add significant weight, cost, and complexity. Non-congenital amputees also make up the vast majority of the limbless in places like India. The reference to blue-collar lifestyles suggests prioritization of high force outputs rather than dexterity and precision of grips.

2) Unilateral transradial amputees with white-collar lifestyles in India.

Similarly, selecting unilateral, transradial amputees greatly simplifies the design and biointerface of the prosthetic. The key distinction here is the shift to a white-collar life. With this comes an increase in need for precision grip over pure grip strength. Moreover, the robustness of the hand, while still important, is not as critical in design. It can be expected that a white-collar lifestyle will result with force exertion on the prosthetic. Overall, an entirely different subset of activities and the motions of daily living would need to be considered to design for these customers.

3) Unilateral transhumeral amputees with blue-collar lifestyles in India

Similar to the first option, but this case of user needs functionality of an elbow joint. The elbow joint could be body-powered or EMG controlled. It provides a very interesting design challenge on top of the already difficult mechanism design required to make an effective prosthetic hand.

3.1.2 Customer Empathy

In order to obtain a more hands-on view of the needs of amputees, the project team participated in "No Hand Day". In this experiment, each member of the team restrained their non-dominant hand for an entire day. Amputees generally gain dominant-hand

level functionality with their amputated hand in about three months (if it was not their dominant hand already) [53]. As a result, the group was able to simulate a one-handed experience for a brief period of time.

In this experiment, activities such as cooking, typing, opening things and carrying things were identified as challenging. More surprisingly easy activities included opening bottles or caps. The Otherwise, the group noticed that cosmesis and comfort are critical, and wearing a bad prosthesis can greatly inhibit general life function. Overall, this customer empathy exercise helped the group understand the very surface of what inconveniences and frustration that an amputation can cause to daily life. It also highlighted how just a bit of extra support from a non-dominant hand can be critical in daily tasks, and served as motivation to stay in tune with user needs throughout the design process.

3.1.3 Conceptual Requirements

Based on the research conducted we had an understanding of the general structure of the needs to develop for this project. Table 6 outlines the needs that fuel the product specifications outlined in Chapter 3.2. These needs had been developed in collaboration with BMVSS and in particular Dr. Pooja Mukul; interview summaries can be found in Appendix J.

Table 6: Consolidation and prioritization of customer needs

Need Category	Need Statement	Priority (1-5)
Functionality	*Need 1.1* The customer should be able to execute: 1. Pinch grip (as to hold onto something with weight) 2. Open handed grip (to perform operations such as opening door knobs and and grabbing oversized objects)	4
	Need 1.2 The customer should be able to pick up objects less than 10 lbs.	3
	Need 1.3 The customer can control the prosthesis with negligible energy excursion	5

	Need 1.4 The prosthesis should reliably reflect user intention	5
Safety & Maintenance	*Need 2.1* The customer must be safe from accidental shortage of the battery as the hand interacts with outside components	5
	Need 2.2 The customer must be able to get their prosthesis wet without damaging electrical components or damaging joints	4
	Need 2.3 The customer must be able to replenish battery power with easily accessible and affordable energy sources	3
Accessibility (Manufacturability) & Cost	*Need 3.1* The hand can be made from parts and processes easily accessible or installable in India	2
	Need 3.2 The customer should be able to obtain the hand for less than $500	5
	Need 3.3 The customer can learn to interface with the hand in under 3 days.	2
Appearance & Social Acceptance	*Need 4.1* The hand must look like it fits the users body (texture, shape and color)	4
	Need 4.2 The hand must be non-invasive and feel like an extension of their body after training and adjustment	3
	Need 4.3 The biointerface must be subtle or easily disguised.	3
User Comfort	*Need 5.1* The entire system should be wearable on a daily basis without creating a negative biological response or reaction.	5

The results that were gathered were both enlightening and encouraging. The direction in which we wished to take this project became much more clear and it was apparent that we would be able to have a large impact on a struggling subsection of society. At this point in time, we looked to shift our focus to the design phase of the project where we could begin to intertwine the needs of the customer with our own technical expertise.

It became clear that there were a few key customer needs that were / still are paramount to the success of our frugal electric prosthetic hand. The prosthetic needed to be accessible to those who can't afford to pay for a high cost prosthetic. It came to our attention that the lack of access to these high cost prosthetics is largely due to the fact that amputees (especially those without a functional prosthetic) cannot work in a way that would financially support such a purchase. Thus, they are stuck without any options to advance themselves in society. We sought to eliminate this disadvantage and deliver a low-cost product without sacrificing any other needs of the Indian user. Additionally, the prosthetic must be versatile, functional, yet robust. As Dr. Pooja Mukul said, "The project must also be performance driven" [53]. We needed to close the gap between low cost body powered prosthetics and high cost prosthetics with extravagant functionality by delivering a simpler solution with a very competent grip and interface. Obtaining basic functionality was critical before focussing on any additional items to be included in the design. This ensured that we could meet the robustness criteria and fully analyze the potential longevity and durability of the basis for our device. Lastly, the prosthetic must be accepted into society and accepted by the user. Social stigmas around amputees in India are unfortunate, but must be dealt with. By delivering a product that looks and feels natural, the user can feel confidently included in their own society. In order to deliver on this project and final product, it was critical that our project team kept these primary needs in mind.

3.2 System Level Design Requirements

3.2.1 Product Specifications

The required functions and constraints for the product are outlined in Chapter 2.2. Knowing the needed functions, defining the necessary product specifications was paramount to beginning the actual design process. By consolidating customer needs identified through BMVSS and information from other research, we were able to more clearly benchmark the relevant metrics for the prosthetic hand we sought to develop. Each metric, as seen in Table 7, has associated marginal and ideal values. The marginal value column established a baseline performance parameter value that

needed to be met. The ideal value column established an optimum value that if met, helped to ensure that our product would exceed expectations. By setting up different ranges for the metrics, we created a way to gauge the success of each component that contributed to the overall product.

Table 7: Product specifications

Need	Priority	Metric	Units	Marginal Value	Ideal Value
1.2	3	Grip Force	N	22-67	44
3.2	5	Total Parts Cost	USD	<400	<250
1.3	5	Total mass of hand	lbs	0.7-1.4	0.9-1.1
1.4	4	Total Cycles to Failure	#	1.5 million	2 million
2.3	3	Battery life	hrs	>8	>40
4.1	4	Total volume (box in which the hand fits)	in x in x in (lwh)	7.5 x 7.5.x 1.5	7.5 x 6.0.x 1.25
4.1	4	Time to close hand from fully open position	s	1	0.5
2.4	2	Required maintenance period	times/year	1	0.2
1.4	4	Compressive strength	lbs	10	20
3.5	2	Operating Temperature	°F	40 - 120	-20 - 450
3.4	3	Number of Actuators	#	<5	1

3.2.2 Benchmarking

As discussed in Chapter 1.2.2, there is a broad range of myoelectric and body powered existing prosthetic technologies both on the market and developed for research. Table 5 shows the benchmarking data for some of these existing options. This can be contrasted with the specifications outlined in Table 8.

Table 8: Summary benchmark data on existing prostheses [22-43]

Prostheses	Cost (USD)	No. Joints	No. Actuators	Weight (lbs)	Grip Force (lbs)	Active Grip (Y/N)	Anthropomorphism (1:5)
iLimb Quantum	80,000	11	6	1.10	28.3	Y	5
Ottobock Michelangelo	60,000	6	2	0.93	15.7	N	5
Taska	35,000	9	6	-		N	4
Ottobock SensorHand	4,700	3	1	1.01	22.5	Y	3
Openbionics Hero Arm	2,000	11	5	2		N	4
Dextrus	1,100	14	6	1		Y	2
Tact	250	11	6	0.77	3.6	N	2
Exii Hackberry	200	14	3	1.43		N	3

The hands outlined in Table 8 fall into a couple of different main categories. iLimb Quantum, Ottobock Michelangelo and Taska would fall into the category of high end myoelectrics. While the functionality and anthropomorphism of these hands is great, they have very high cost and many actuators. The Ottobock SensorHand fits closely with our project. It has just one actuator, and is myoelectrically controlled. However, the cost is much greater than our specification. Some of the other hand (Tact, Hackberry) are interesting open source 3D printed research projects. 3D printing technology is not currently widely spread in India and not practical for mass manufacturing applications.

3.3 System Level Design

As discussed, the product is designed for unilateral, transradial amputees living white-collar lifestyles in India. At the outset, the team roughly outlined what subsystems the overall system may be comprised of in order to have a better idea of how to design a

prosthetic hand to meet the known needs. The systems sketch in Fig. 22 illustrates how each original subsystem will contribute to the overall functionality required at the system level.
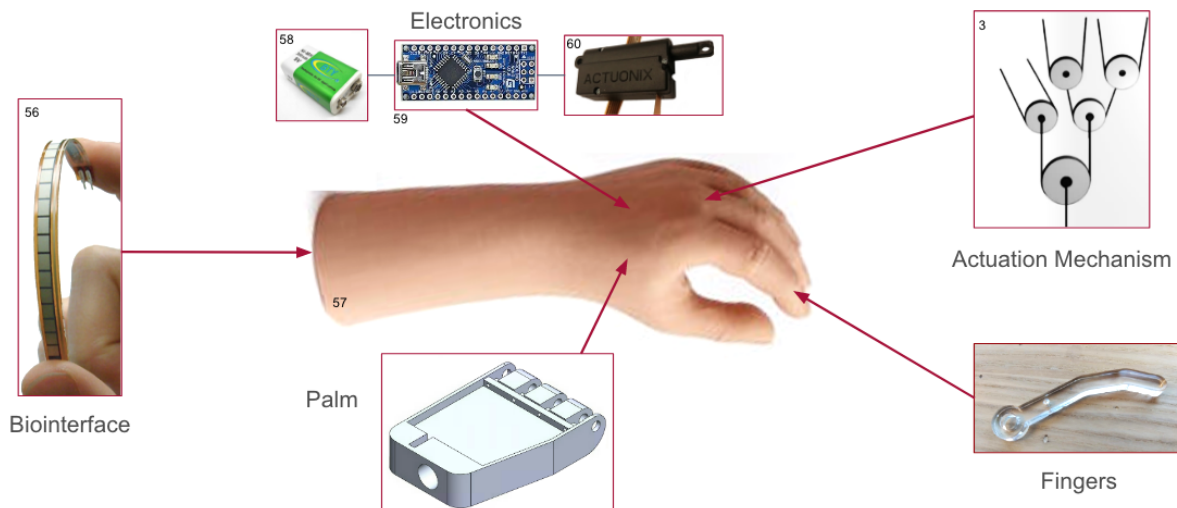
Fig. 22: HELP Hand systems level sketch

When the user goes to activate the HELP hand, they will move their body in a pattern recognized by the software (this may be a simple flex). The electrode sends the signal to the microcontroller, and after processing, the microcontroller sends a pulse to the motor such that the hand opens and closes (the hands default position is closed). This motor is powered by a battery mounted to the prosthetic interface. The motor interfaces with a tendon-driven actuation mechanism which determines the open or closed position of the hand.

The block diagram in Fig. 23 provides an overview of the whole system and how the various subsystems interact with one another.
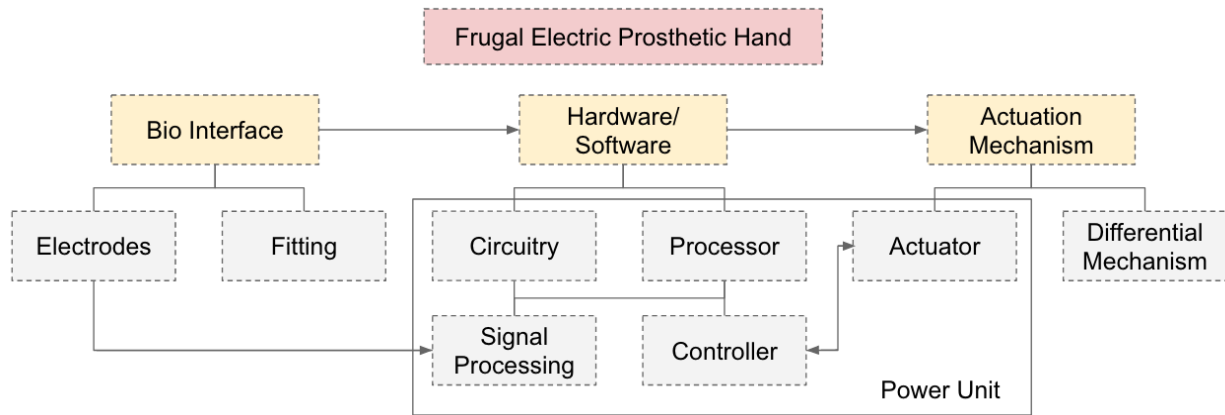
Fig. 23: Systems level block diagram

Chapter 4: System Level Decisions

The project was initially split up into two overall systems at the systems level. For both the mechanical and biointerface sides of the design, initial requirements and specifications were detailed such that the team could analyze possible solutions to fulfilling customer needs.

4.1 Mechanical System

4.1.1 Introduction and Requirements

The role of the mechanical system was to translate a bio-input into the secure grasping of an object.

The mechanical system was most importantly required to support the anthropomorphism of the device, while static or in movement. Furthermore, high performance of the device by reliably completing a broad range of tasks was required. The system also had to be easily manufactured and robust enough to withstand long term, heavy use.

4.1.2 Options and Tradeoffs

To begin with the mechanical system-level design, we had to decide on what family prosthesis actuation we would pursue.

There are two primary types of devices, compliant and non-compliant. Complaint devices use a single actuator to generate multiple degrees of freedom such that the hand will comply to, or form around, the object being grasped. In contrast, non-compliant hands produce a single rigid grabbing motion. Advantages of each method are summarized in Table 9.

Table 9: Comparison of compliant and non-compliant actuation

Advantages of Compliance	Advantages of Non-Compliance
● Greater variety in grasp leads to reliable grasping of a wider variety of objects ● Increased contact area produces increased friction between the glove and object, reducing chances of slip ● Multiple degrees of freedom promote high anthropomorphism	● Single degree of freedom can be achieved using simple mechanical system ● Application of force to a single motion produces high pinch forces ● Consistency in grasping motion produces more predictable hand function

Within these two categories, seven options were identified (see Fig. 24).
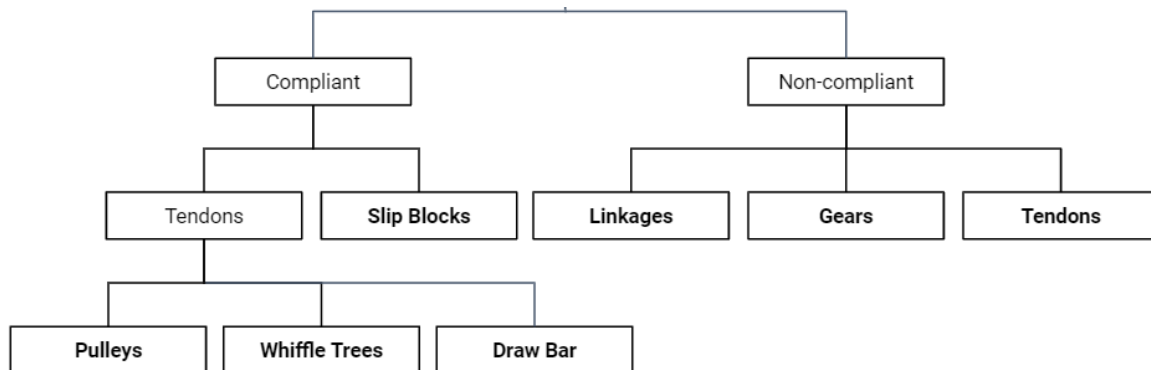
Fig. 24: Mechanical actuation system options

4.1.2.1: Compliant Pulley System

In a compliant pulley mechanism, tendons modeled by rope are run through a system of pulleys as shown in Fig. 25. This allows for compliant movement between fingers attached to the upper four tendon ends while requiring only a single actuator to pull on the bottom tendon end.

The use of tendons promotes anthropomorphic movement by enabling incremental movements similar to human movement. However, the resistance within and between fingers must be finely tuned to achieve smooth motion. Additionally, a primary concern

within tendon actuation prosthesis is fatigue of the tendons and/or tendon channels. However, extensive research has been conducted at other universities documenting the use of specific materials, coated cables, and protected channels to achieve a high number of cycles before failure.

A primary benefit of the pulley system is that it achieves compliance through ultimately a simple design that requires a low total number of pieces, a low level of precision, and no intentional tuning of the force distribution between fingers. The system is also lightweight and takes little space. However, the compliant pulley system also requires the selection of durable tendons and pulleys. Furthermore, the initial assembly of the pulley system would contribute to the difficulty of the manufacturing and assembly process.
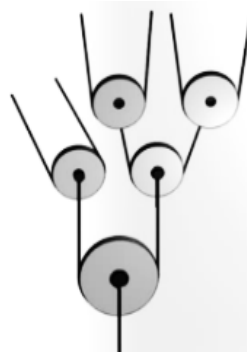
Fig. 25: Compliant pulley mechanism [3]

4.1.2.2: Compliant Whiffletree System

In a compliant whiffletree mechanism, a series of whiffletrees are constructed so as to convert the pulling of a single tendon at the bottom is converted into compliant movement in the top tendons. A whiffletree consists in tendons being tied to either end of a pivoting bar as shown in Fig. 26. The single bottom tendon is then tied in the middle.

A primary benefit of this system is that it allows for tuned compliance; by altering the relative distance between each of the upper tendons and the single bottom tendon, the force distribution between the two upper tendons can be controlled. However, this also

requires additional precision and tuning. There are also more total pieces involved in the system.
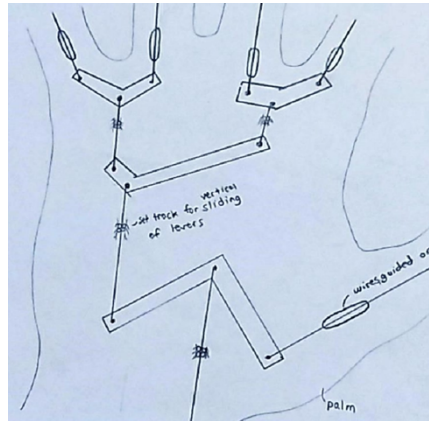
Fig. 26: Compliant whiffletree mechanism

4.1.2.3 Compliant Draw Bar

In our concept for a draw bar mechanism, the motor is connected to a draw bar fitted with slip clutches for each finger (see Fig. 27). The slip clutch rotates with the draw bar until a threshold torque is applied to the clutch, at which point the slip clutch allows for free rotation of the motor. All fingers would be attached to its respective slip clutch via a looped track. This system will therefore lead to the distribution of force between all fingers until each is at the threshold torque such that each finger can move until fully closed around the object, at which point the threshold torque would be applied to each finger.

A primary benefit of this system is that it takes less physical space to achieve compliance. Furthermore, it requires fewer interreliant and moving components. This might make the construction of such a mechanism simpler. However, it was also a design that we had not seen implemented before, making its challenges less well known. Difficulty in achieving the correct threshold torque and securing the connection between the slip clutches and the fingers were anticipated challenges. Most importantly, the basic function of the slip clutches in allowing for compliant movement would need to be proved in a physical model before this design was pursued.

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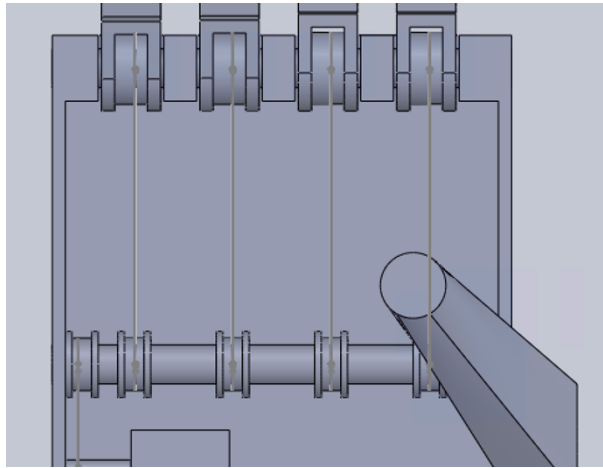
Fig. 27: Compliant draw bar mechanism

4.1.2.4 Compliant Slip Blocks

In a slip block mechanism, torque is transferred along the finger members as they come into contact with an object. The transfer occurs when a slip block is compressed by the object, effectively causing the next member to rotate because the previous member no longer can (see Fig. 28).

A primary benefit of the slip block mechanism is that it provides passive adaptation while maintaining both a low weight and a small profile [16]. It also avoids many of the complications present in the use of tension cables, namely the lack of mechanical advantage or torque, the wear incurred by sliding cables, and the interdependence of all fingers. However, it requires many precisely fitted components and adds complexity to the fingers. It also only achieves compliance within, rather than between, fingers.
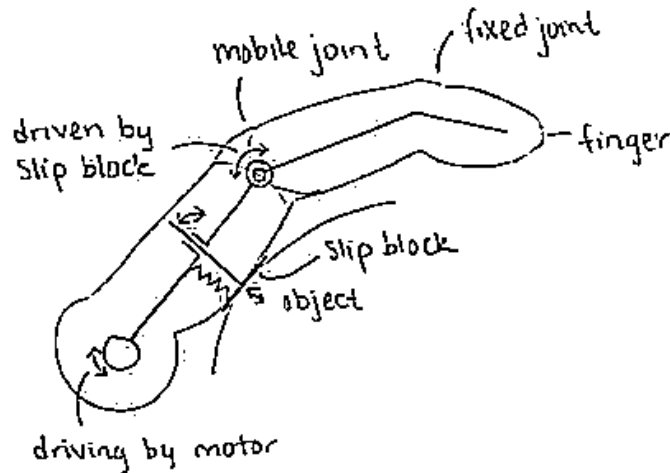
Fig. 28: Compliant slip block mechanism

4.1.2.5: Non-Compliant Linkages

In a linkage system, stiff bars are connected such that the rotation of a single original bar is translated into the siff movement of the rest of the actuation mechanism and fingers.

A primary benefit of the linkage system is that it can produce somewhat complex movement in the fingers. Additionally, because all components can be metal rods, the mechanism can be durable and construction can be simple. However, it can be exceedingly difficult to create a linkage mechanism that will produce exactly the desired motion. Furthermore, because all components are rigid and are expected to rotate, it can be difficult to fit the linkage mechanism into a small palm-shaped package.

4.1.2.6: Non-Compliant Gears

In a gear based system, a gear train translates the motion of the motor into the rotation of one or more fingers. Gears can also be used to connect the rotation of different sets of fingers, for example between the index and the thumb. Finally, the gears can be used to modify the angular speed and torque of the fingers.

A primary benefit of the gear based system is that it is a relatively compact and simple system. The strength of gears also supports the transmission of high torques and

consequently can produce high pinch forces. However, gears must also be sized and meshed very carefully, making manufacturing and construction difficult. Furthermore, custom gears can be very expensive, so it is ideal to use only standard shapes and sizes.

4.1.2.7: Non-Compliant Tendons

Non-compliant tendon systems link fingers to the axle using a rope to model a tendon. Each finger is linked to the axel independently, but all are solidly fixed such that non-compliant movement results.

A primary benefit of the non-compliant tendon system is its simplicity; it requires few parts, and construction is both simple and moderately imprecise. However, the use of tendons makes the system less durable. Also, the reliance on a moment arm about first the motor shaft and then the finger shaft makes the size limitations of the prosthesis a challenge.

4.1.2.8: Tradeoff Summary

A summary of the advantages and disadvantages of the identified options is presented in Table 10.

Table 10: Tradeoff summary of actuation mechanisms

Mechanism	Advantages	Disadvantages
Compliant Pulleys	• Anthropomorphic • Moderate mechanical simplicity • Low precision required • Lightweight and small	• Tendon fatigue • Complex assembly • Inefficient transfer
Compliant Whiffletrees	• Anthropomorphic • Allows for tuning • Lightweight	• Moderate precision • Moderate to high mechanical complexity
Compliant Draw Bar	• Anthropomorphic • Lightweight and small • Simple construction	• Precise and complex design required • Unknown

Compliant Slip Blocks	● Efficient force transfer ● Independence of fingers	● Complex design ● High precision required ● Large and heavy ● Permits anthropomorphism only within rather than between fingers
Non-Compliant Linkages	● Durable ● Simple construction	● Precise design required ● Large and difficult to fit in palm space
Non-Compliant Gears	● Small and simple ● Efficient force transfer ● Durable and strong	● Precise manufacturing and construction required ● Limited to off the shelf components
Non-Compliant Tendons	● Moderate mechanical simplicity ● Low precision required ● Lightweight and small	● Tendon fatigue ● Inefficient force transfer

4.1.3 Design Decision

These seven options were then scored by each team member independently using 14 weighted criteria spanning over 4 main categories. As can be seen in Table 11, the compliant method using tendons and pulleys ultimately scored the highest and was therefore our chosen mechanical system approach. The complete decision matrices can be found in Appendix E.

Table 11: Mechanical system decision matrix results

Rank	Score (1-5)	Actuation Concept
1	3.56	Compliant - Tendon W/ Pulleys
2	3.48	Noncompliant - Tendon
3	3.08	Noncompliant - Linkage
4	3.06	Compliant - Tendon W/ Whiffletrees
5	2.87	Compliant - Linkage Lever

| 6 | 2.53 | Noncompliant - Gear |
| 7 | 2.28 | Compliant - Slip Block |

4.2 Biointerface System

4.2.1 Introduction and Requirements

The biointerface subsystem is responsible for integrating user intention and mechanical actuation. It takes a user generated input to induce the motion of the prosthetic hand, thereby allowing for electrical control of the prosthesis.

In designing the biointerface, the requirements were as follows: the biointerface had to be anthropomorphic, comfortable for long term wear, visually subtle, electrically powered, and require little physical force to operate. Most importantly, the biointerface had to be reliable in that user intention and mechanical actuation matched in order to reduce unintentional actuation or failed actuation with intention. These criteria addressed customer needs 1.1, 1.3, 1.4, 4.3, and 5.1 (as noted in Table 6). See Appendix E for the decision matrix used and the determination of importance between stated criteria, and Appendix I for an expanded description of each criterion.

4.2.2 Options and Tradeoffs

The three options explored for a biointerface control system were electromyography (EMG), mechanomyography (MMG), and flex sensor control.

4.2.2.1 Electromyography (EMG)

Electromyography is the use of electrodes to detect muscle movement. When neurons fire to trigger the contraction of muscle cells, small electrical voltages are created by an exchange of ions between the cell and its surroundings. The cumulative electrical potential between many neurons can be detected by electrodes such that muscle

contractions cause jumps in voltage. Thus, EMG can be used to read muscle contractions.

As previously discussed, EMG control of prostheses presents significant challenges, mainly regarding the importance of electrode placement and contact in collecting useful and reliable EMG signals. With the Myoware board, three electrodes are needed at all times: two electrodes must be fixed at a certain distance from one another in order to match the snaps on the Myoware board, while a third must be placed away from the muscle being measured. Placement of these electrodes is critical in obtaining reliable data, and will be subject to user error as the prosthesis is taken on and off on a daily basis. If the electrodes are placed incorrectly, it is likely that the control of the prosthesis will be unreliable because data values collected will not be consistent from day to day.

Secondly, the contact area between the electrodes and the skin needs to be properly maintained. In the context of this project, this requires that the electrode remains tightly in contact with the user throughout the day, regardless of sweat, humidity, and other environmental factors. EMG signals are most susceptible to interference caused by such factors, specifically because of the contact area requirement.

Finally, the signal processing required to effectively utilize EMG signals can be extensive and complicated. Before they can be useful, EMG signals must be rectified, windowed, and often transformed using a fast fourier transform. Additionally, because muscles are used in every motion, regardless of whether or not the contraction is intentional, the use of EMG control requires thorough isolation of intentional movement from all movement.
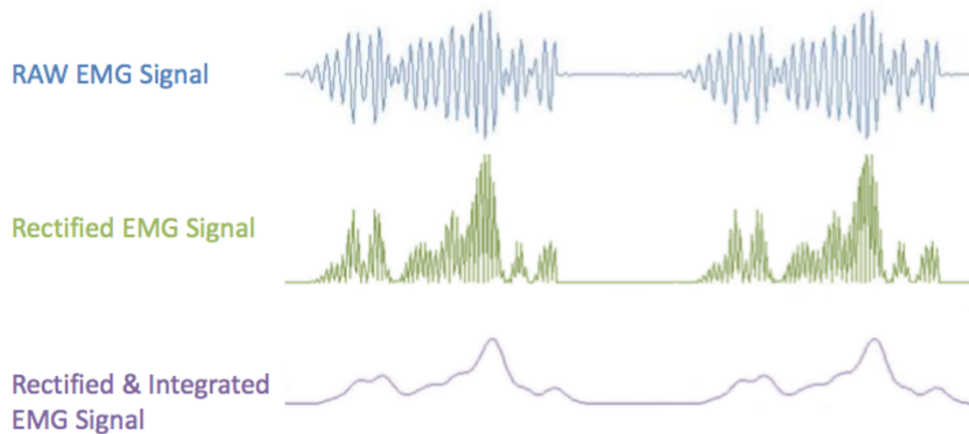
Fig. 29: EMG signal processing as completed by MyoWare, two muscle contractions visualized [61]

The primary benefit of using EMG control is that it isolates the signal collection method to the same limb that the prosthesis is worn on. In other words, it does not constrict any other parts of the body and can be actuated without any additional physical motion. When done reliably, actuation of the prosthesis is easy and almost undetectable by anyone except the user.

4.2.2.2 Mechanomyography (MMG)

Mechanomyography was considered for this project as an alternative that might address the major challenges with EMG control. Specifically, as stated previously in the literature review, an MMG system would reduce susceptibility of the sensors to physiological factors such as sweat. Additionally, because an MMG arm-band or other wearable device would depend less on close contact with the skin, an MMG control system would likely be more comfortable to wear than an EMG wearable.
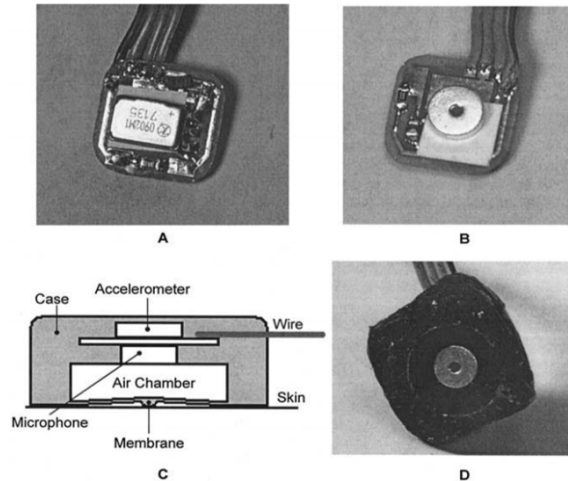
Fig. 30: An example of an MMG control system [62]

However, because MMGs utilize an array of sensors, the design of an MMG system would be ultimately more complex than that of an EMG control system. This is further complicated as MMG use for prosthetic control is not as widely explored as EMG control, and the current designs are not well documented. Additionally, although MMGs are less susceptible to physiological interference, they require more signal filtering and processing in order to differentiate between intentional motion and environmental noise. The signal processing load would require determining what exactly constitutes an intentional movement, while filtering out all of the possible environmental factors that could contribute to noise.
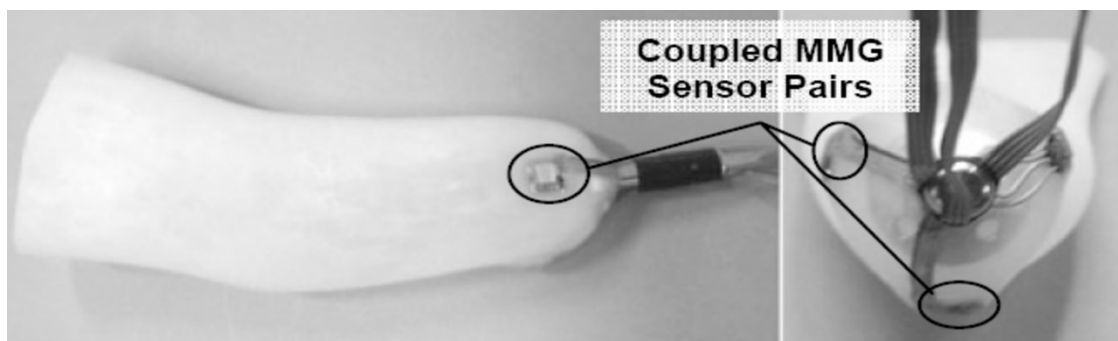
Fig. 31: MMG sensor placement on the distal end of the stump [63]. Each coupled MMG sensor pair was defined by a microphone and an accelerometer.

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Under the umbrella of MMGs, the use of accelerometers and inertial measurement units (IMUs) to relate physical body motion to hand opening or closing was also considered. It was recognized that often times, when a person would like to grab something, he or she will likely extend his or her arm immediately prior to opening his or her hand. Ultimately, this option was not pursued because the relationship between two body motions was too complex to match simply.

4.2.2.3 Flex Sensor Control

The final option seriously considered for use in a biointerface was the use of flex sensors in such a way as to combine body-powered and electric prostheses. As stated previously, body-powered prostheses utilize a cable stretched between shoulders that changes in response to internal shoulder rotation. As the user rotates the shoulders in, the cable stretches and closes the prosthetic hand; as long as the user would like the hand to remain closed, he or she must also keep his or her shoulders in the internally rotated position. The two largest complaints with body powered prostheses, as described by Dr. Pooja Mukul, a prosthetist and point of contact at BMVSS, are the physical restriction of the upper back and shoulders and the physical strength required to produce an adequate and sustained prosthetic grip force.

Fig. 32. Hand-drawn sketches of how a flex sensor would be placed in order to be easily manipulated by the user. Such control systems would mimic body-powered prosthetics but would require little force from the user to maintain hand grip force.

The use of a flex sensor would allow for a reduced signal processing load, as compared to an EMG control system, while also reducing the amount of noise that would have resulted using an MMG system. In this way, a flex sensor dependent control system would provide the ideal amount of a signal processing that is technically feasible.

On the other hand, the use of a flex sensor, body-powered like control system does not address customer need 4.3, as depending on where the fabric is placed, the system will physically restrict other parts of the user's body. As this was one of the major complaints with body powered prosthetics, the design of the flex sensor subsystem would need to take into account the distance and body parts over which the fabric is placed.

4.2.2.4 Tradeoff Summary

A summary of the advantages and disadvantages of the identified options is presented in Table 12.

Table 12: Tradeoff summary of biointerface options

Biointerface	Advantages	Disadvantages
Electromyography (EMG)	- Confined to amputated limb - Subtle signal trigger needed	- Signals generated from everyday movements - Relies on clean skin/electrode interface - High signal processing load - Possible biocompatibility issues
Mechanomyography (MMG)	- Reduced reliance on skin/electrode interface - Confined to amputated limb	- High signal processing load - High sensor complexity
Flex Sensors	- Not reliant on skin/electrode interface - Reasonable Signal Processing Load - Simple construction	- Potentially restrictive across the body - Less visually subtle

4.2.3 Design Decision

Based on the decision matrix in Appendix E, and the criteria stated here, the design team decided to primarily move forward with an EMG control system. Using the decision matrix, an EMG control system earned a score of 3.145, while a flex sensor system scored 3.09, and an MMG system scored a 2.18. Additionally, because the differences between an EMG control system and resistive fabric control were minimal, the team also considered flex sensor control as a design option. Ultimately, the prototyping and iteration phase of the design project proved that EMG control would be unfeasible for this project, and the final design of the biointerface uses flex sensor control.

Table 13: Biointerface system decision matrix results

Rank	Score (1-5)	Control System
1	3.14	Electromyography (EMG)
2	3.09	Flex Sensors
3	2.18	Mechanomyography

Chapter 5: Biointerface Subsystem

5.1 Introduction and Requirements

The biointerface subsystem had two distinct phases. The first phase of the design utilized EMG control using the Myoware signal processing board and wet electrodes as a signal acquisition method. When prototyping indicated that the required signal processing load was too high for the scope of this project, the second phase of the design began. During the second phase of the design, flex sensors were pursued as a signal acquisition method. Ultimately, flex sensors were used as the final biointerface.

5.2 Options And Tradeoffs

To create an initial design for myoelectric control, electrode type and signal processing system would both have to be decided from available market options.

5.2.1 Electrode Type

Surface EMG signals can be collected by both wet electrodes and dry electrodes. Wet electrodes are electrodes that rely on a hydrogel interface between the metal electrode and the skin; this hydrogel increases conductivity and creates a more reliable interface for the electrical potential to travel through. Wet electrodes are cheap, disposable, and single use. They work well in instructional labs and are easily applied.

The primary benefit of using wet electrodes is that they are designed to integrate easily with commercially available EMG processing systems. Additionally, because they are only about 15 cents per electrode, they are low cost. However, disposable wet electrodes are a relatively unsustainable option for a long term prostheses, as the electrodes would need to be replaced on a daily basis.

A more sustainable option for electrodes is dry electrodes. Dry electrodes are electrodes that do not rely on a hydrogel interface between the skin and the electrode,

and are most commonly used in commercial myoelectric prostheses. Unlike wet electrodes, dry electrodes are not cheap and single use.

5.2.2 Myoware

To reduce the signal processing load associated with EMG data collection and use, the first prototype utilized the Myoware Signal processing board. The Myoware board is a commercially available signal processing unit, sold for less than $40, that collects, filters, and rectifies EMG signals (see Fig. 33). The board is driven by any Arduino microcontroller, snaps directly to the standard wet electrode size, and is relatively compact. The Myoware board also has cable extensions that allow the user to use the signal processing features without having to wear the board directly on the muscle of interest.

Fig. 33. Myoware board [64]

5.3 Initial Design Description

The initial design of the EMG control system utilized the Myoware signal processing board with disposable wet electrodes from 3M. To use the Myoware board, two disposable wet electrodes are attached directly to the board, and one is attached to the black ground cable. The board is then placed on the muscle of interest, with the ground cable attached to a location that has minimal muscle, like the bony part of the elbow. The muscle of interest can be either along the forearm or along the bicep, as long as

the muscle is large enough to have a significant contraction. For initial testing, we alternated between placement on the inner bicep and placement on the inner forearm.
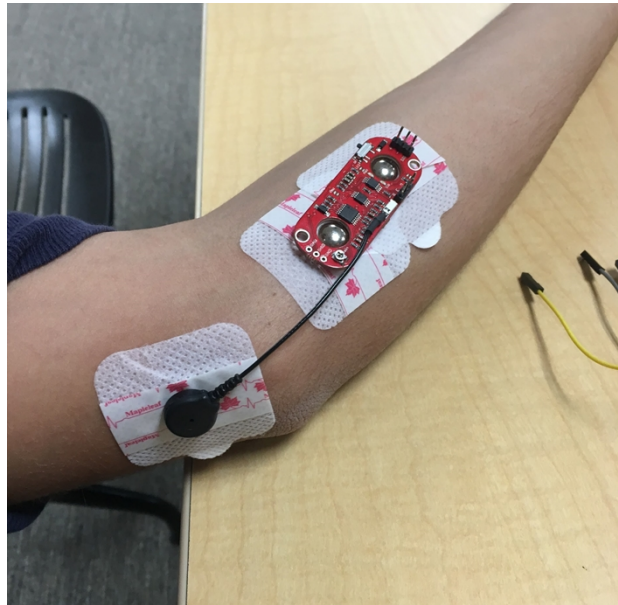
Fig. 34: Myoware placement on the forearm. Placement of the two adjacent electrodes must be on the muscle being measured, while the third electrode (shown here as a black snap) is placed away from the muscle and serves as ground.

Once placed on the arm, the Myoware board is then connected to an Arduino microcontroller. A simple analogRead() function can be used to collect the signals from the Myoware board, which can then be plotted using the Serial Plotter to visualize muscle contractions. The initial prototype used an Arduino Leonardo.
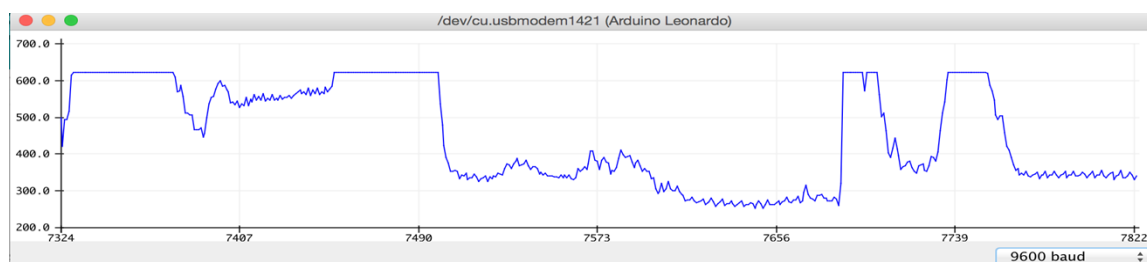
Fig. 35: Arduino serial plotter using the MyoWare signal processing board

Initially, a simple threshold control scheme was used to distinguish between intentional muscle contraction and unintentional muscle contraction. See Fig. 36 for the Arduino code for basic threshold control. With the control scheme pictured, three values were stored and averaged, with data points collected every 10 ms. By simply rewriting four basic variables with new data points, the averaged window overlapped the previous window by three data points, taken over 30 ms. If the average of the four data points exceeded a threshold value of 600, the hand would be actuated (represented by the lighting of an LED in the prototyping phase).

```
const int threshValue = 600;
int pastValue1= 0;
int pastValue2 = 0;
int pastValue3 = 0;
int pastValue4 = 0;
int currentValue = 0;
int avgValue = 0;

void setup() {
  // put your setup code here, to run once:
  pinMode(LED_BUILTIN, OUTPUT); // Set up an LED to simulate actuation of the hand
  Serial.begin(9600);


}

void loop() {
  // put your main code here, to run repeatedly:
  // Read a sensor value you and assign it to a variable.
  // Store past 5 values and average 5 values.
  pastValue4 = pastValue3;
  pastValue3 = pastValue2;
  pastValue2 = pastValue1;
  pastValue1 = currentValue;
  currentValue = analogRead(A3);
  avgValue = (pastValue4 + pastValue3 + pastValue2 + pastValue1 + currentValue)/5;

  // Simulate actuation of the hand if the threshold is reached.
  if(avgValue < threshValue)
  {
    digitalWrite(LED_BUILTIN, LOW);

  }
  else
  {
    digitalWrite(LED_BUILTIN,HIGH);
    // delay(250);

  }

  Serial.println(analogRead(A3));

  delay(10); // delay for 1/100 of a second
```

Fig. **36:** Preliminary threshold control with Myoware

5.4 Prototyping Results

In initial testing, simple basic threshold control proved insufficient to properly pick out peaks associated with intentional muscle contraction. Five data points, collected and averaged every 50 ms, was not sufficient to catch every intentional muscle contraction. In response, the team opted to pursue an array based control scheme in which a larger array of values was collected. The array of values was then segmented into three different portions and the average of each portion was compared. As seen in Fig. 37, the code was broken into three main portions: arrayBuilding(), arrayAveraging(), and arrayComparison().

```
int dataPoints[600];
int currentValue = 0;
int threshValue = 200;
double firstThirdSum, secondThirdSum, thirdThirdSum;
double firstThirdAverage, secondThirdAverage, thirdThirdAverage;

void setup() {
  // put your setup code here, to run once:
  pinMode(LED_BUILTIN, OUTPUT);
  Serial.begin(9600);

}

void loop() {
  arrayBuilding(); // after this function is called, you have an updated
  // array called dataPoints
  arrayAveraging();
  // takes array averages
  arrayComparison();
  // compares arrays and lights up LED under certain conditions

}
```

Fig. 37: Array based threshold control. Fig. 38-40 display the three subsequent functions.

In the arrayBuilding() portion of the code, an array of 600 data points was established. For each loop of the code, each Myoware value stored in the dataPoints[] array was shifted to the next position, and the first position of dataPoints[] was filled with the

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current Myoware output value. This built an array of 600 data points that was constantly shifting to include a new Myoware value.

```
void arrayBuilding() {
  currentValue = analogRead(A3);

  for (int a = 0; a < sizeof(dataPoints) / sizeof(int) - 1; a++) {
    // have to do sizeof(int) because sizeof(dataPoints) will return
    // bits not actual values in array
    dataPoints[a + 1] = dataPoints[a];
    // shifts everything over one
  }
  dataPoints[0] = currentValue;
}
```

Fig. 38: Array building for array based threshold control

In the arrayAveraging() portion of the code, the dataPoints[] array was sectioned into thirds and the average of each third was taken. By averaging each third of the array, the average was collected over a larger value of data points that could constantly shift. This averaging was similar to the simple threshold control pictured in Fig. 39.

```
void arrayAveraging() {
  firstThirdSum = 0;
  secondThirdSum = 0;
  thirdThirdSum = 0;
  firstThirdAverage = 0;
  secondThirdAverage = 0;
  thirdThirdAverage = 0;

// For the first third, second third, and third third, takes the sum of each third
// once sum is totaled, average is caculated for each third.

  for (int a = 0; a < sizeof(dataPoints) / sizeof(int) - 1; a++) {
    if (a < ((sizeof(dataPoints) / (sizeof(int) )) / 3)) {
      firstThirdSum = firstThirdSum + dataPoints[a];
    }

    if (a < ((sizeof(dataPoints) / (sizeof(int) )) * 2 / 3) && a > (sizeof(dataPoints) / sizeof(int) / 3)) {
      secondThirdSum = secondThirdSum + dataPoints[a];
    }

    if (a < (sizeof(dataPoints) / sizeof(int))) {
      thirdThirdSum = thirdThirdSum + dataPoints[a];
    }


    firstThirdAverage = firstThirdSum / ((sizeof(dataPoints) / (sizeof(int))) / 3);
    secondThirdAverage = secondThirdSum / ((sizeof(dataPoints) / (sizeof(int))) / 3);
    thirdThirdAverage = thirdThirdSum / ((sizeof(dataPoints) / sizeof(int)) / 3);

  }
}
```

Fig. 39: Averaging each third of the constantly changing array

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Once the array was built, sectioned, and averaged, the arrayComparison() portion of the code compared each of the three averages. If the average of the second third of the array was more than double the first average, and the second average was higher than the established threshold value, the actuation occurred. Again, for prototyping purposes, this actuation was represented by an LED.

```
void arrayComparison() {
  if (firstThirdAverage < (0.5 * secondThirdAverage) && secondThirdAverage > threshValue) {
    digitalWrite(LED_BUILTIN, HIGH);
    delay(200); //arbitrary delay
  } else
    digitalWrite(LED_BUILTIN, LOW);


}
```

Fig. 40: Array comparison. If the second third of the array had an average value that was more than double the first average, and the second average was above the threshold value, actuation occurred.

The first part of the if-statement in the arrayComparison() function was written to distinguish between prolonged movement and peaks in the muscle movement. Ideally, intentional muscle movement would be more significant than any movement that would arise from simple muscle contractions that resulted from swinging arms or walking motions.

It was found that this control scheme was insufficient to distinguish between unintentional muscle contractions and intentional muscle contractions. Furthermore, the Myoware unit itself did not have the capability to distinguish between prolonged, unintentional muscle contractions, and short, intentional muscle contractions. In practical terms, this meant that the Myoware unit produced the same signals when a user was swinging his arm versus when the user was sitting down and intentionally contracting his muscle. Returning to address the customer needs outlined in Table 6, it

became clear that the Myoware board would not be a feasible option for data acquisition.
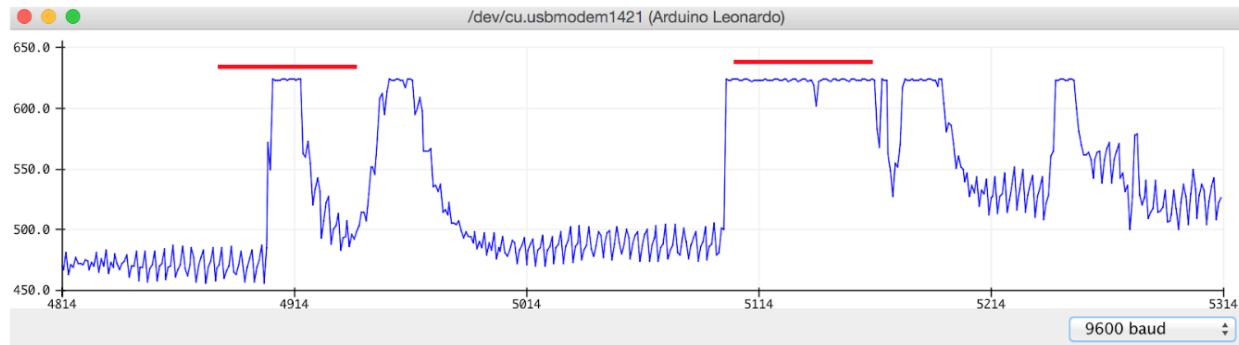
Fig. 41: The first line indicates intentional muscle contraction while sitting down. The second line indicates movement generated from a swinging arm while walking around.

Additionally, biocompatibility and longevity issues arose with the use of disposable wet electrodes. Once placed on the arm, the electrodes were only comfortably worn for five to six hours. Additionally, once the Myoware board was removed from the wet electrodes, a brand new set of electrodes would need to be placed on the skin in order for the board to accurately collect signals. In other words, the electrodes would only collect reliable data for the first attachment point. This was concerning because it reduced the reliability of the data acquisition method, particularly because each user would introduce his or her own error in placing and adjusting the electrodes on a daily basis.

Ultimately, initial prototyping results indicated the myoelectric control using the Myoware unit and wet electrodes was not feasible because of unrealistic signal processing and unreliable data collection. However, to verify that this was not a problem isolated to EMG control, the team also tested EMG data collection using the Myoband. The Myoband is a commercially available armband composed of eight different dry electrodes. With the Myoband, EMG data can be obtained and analyzed, though not as simply as the Myoware and not through an Arduino. In Fig. 42, Myoband data is shown.
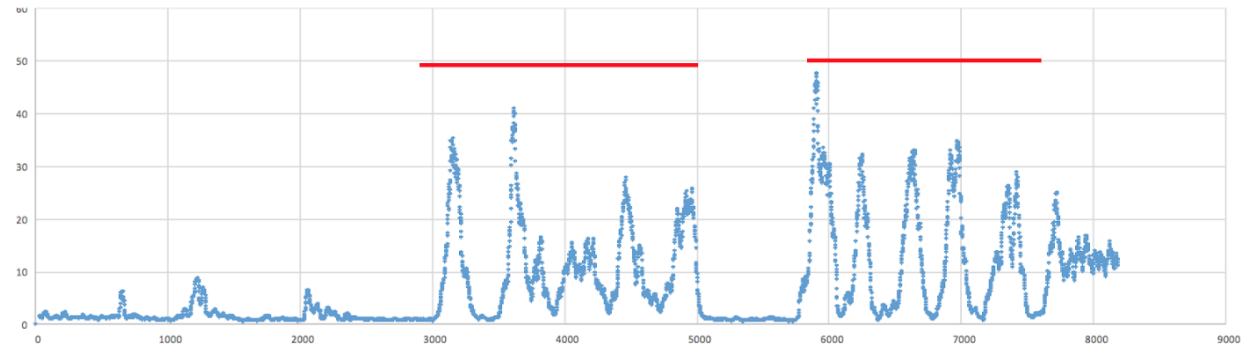
Fig. 42: EMG data collected using the Myoband dry electrodes. Peaks under the first line were generated by a swinging arm, while peaks under the second line were generated by repeated, intentional muscle contractions.

Between both wet electrodes/Myoware and dry electrodes/Myoband, it became clear that EMG control of this prosthesis was an unrealistic design for this senior design project. EMG control, while beneficial for its containment to a singular limb, requires a higher signal processing load than what could feasibly be conducted within a year given the skill set of the four team members.

Returning to the initial biointerface system matrix in Table 13, the team decided to explore flex sensors as the next viable option for the biointerface. Flex sensors did not have many of the problems associated with the myoelectrics, primarily because they did not require a high level of contact between the sensor and the skin. Additionally, the signal processing load was low; a simple voltage divider circuit was used to read changing resistance values of the flex sensor.

Flex sensors (Adafruit Long Flex Sensor) were ordered off Amazon and a basic circuit was built to verify the performance of the flex sensors (see Fig. 43).

66

```
const int FLEX_PIN = A0;
const float VCC = 4.98;
const float R_DIV = 45600.0;
const float STRAIGHT_RESISTANCE = 24300.0;
const float BEND_RESISTANCE = 90000.0;
float flexV, flexR, angle;
int flexADC;

void setup() {
  // put your setup code here, to run once:
  Serial.begin(9600);
  pinMode(FLEX_PIN, INPUT);
  pinMode(LED_BUILTIN, OUTPUT);
}

void loop() {
  // put your main code here, to run repeatedly:
  flexADC = analogRead(FLEX_PIN);
  flexV = flexADC * VCC / 1023.0;
  flexR = R_DIV * ((VCC / flexV) - 1.0);
  Serial.print(flexR);
  // angle = map(flexR, STRAIGHT_RESISTANCE, BEND_RESISTANCE, 0, 90.0);
  if (flexR < 50000.0) {
    Serial.println(" yes");
    digitalWrite(LED_BUILTIN, HIGH);

  }
  else {
    Serial.println(" no");
    digitalWrite(LED_BUILTIN, LOW);
  }
  delay(200);
}
```
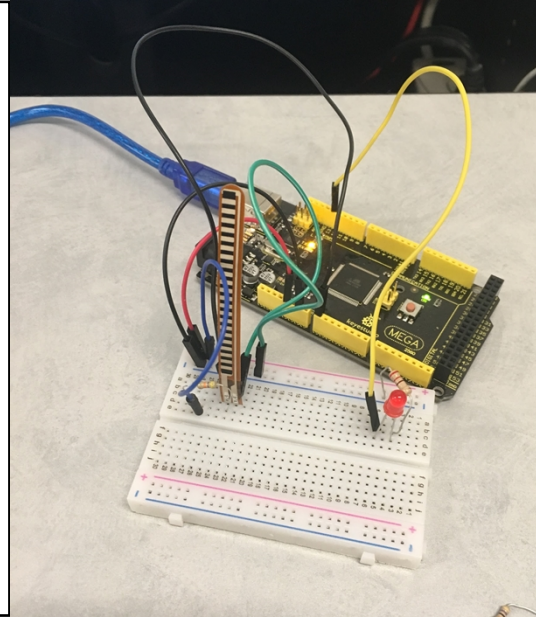
Fig. 43: Basic performance verification of the flex sensors using a voltage divider circuit. 'STRAIGHT_RESISTANCE' and 'BEND_RESISTANCE' variables were measured with a multimeter first and defined accordingly.

After verification of the flex sensor on a breadboard, the flex sensor was sewn into the inner elbow crease of a tight arm sleeve (Fig. 44). When the sleeve was worn, the user could bend his or her arm at the elbow to actuate the hand. At this point, basic threshold control was still being used to determine actuation triggers. This proof of concept was an important point in the iteration process, as it became clear that strategic flex sensor placement was a viable option for user control of the prosthesis.

Fig. 44: Flex sensor sewn into an arm sleeve

At the same time, initial testing indicated that an elbow bend was not always conducive to picking up objects, particularly if the objects were far away and the user had to reach for them. As such, the team selected multiple points on the user's body as actuation locations for sensor placement. Moving forward, it became clear that three locations were to be pursued for sensor placement: the top of the shoulder, between the shoulder blades, and the inside of the elbow.

In order to place and constrain these sensors while still allowing them to bend, "sensor pockets" were designed and sewn to fit the flex sensors. These sensor pockets could then be attached by two velcro connections to a long sleeve compression shirt that could be worn underneath another shirt. Iteration of the sensor pockets can be seen in Fig. 45.
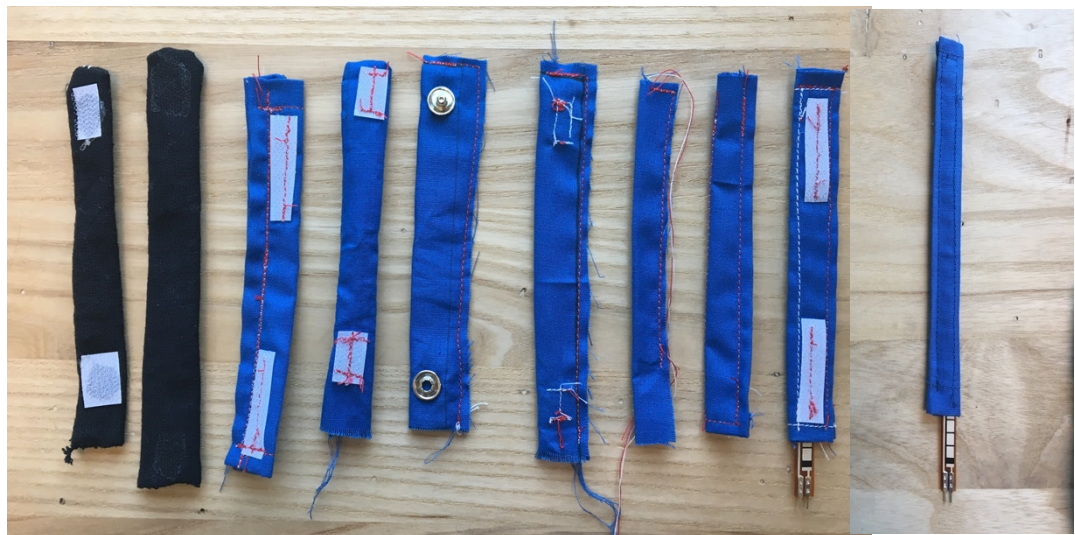
Fig. 45: Iteration of sensor pockets with final design pictured right. The sensor is pictured only partially inserted into the pocket, but fits completely into the pocket itself.

By using two point velcro placement with the sensor pockets, the biointerface becomes modularized and tailored to what the user feels is most comfortable. For example, if the user prefers to shrug her shoulder, she can place the flex sensor on her shoulder (Fig. 46). On the contrary, if the user is most comfortable with body powered prosthesis, the

flex sensor can be placed in between the shoulder blades to mimic the same shoulder flex. Lastly, if the user feels that the elbow sensor is the most helpful placement, the flex sensor can be moved to the inside of the elbow.

Fig. 46: Flex sensor placement (blue) shown on top of the shoulder. A simple, subtle shoulder shrug allows for actuation of the prosthesis.

This provides the distinct advantage of user-focused design. If the user is able to tailor the biointerface to what is most comfortable, it is less likely that the prosthesis will be rejected due to user discomfort. However, the modularity of the design also means that the simple threshold value changes from location to location. The threshold needed to trigger the back flex sensor is much lower than the threshold needed to trigger the flex sensor placed on the inside of the elbow.

To mitigate this, three different control schemes were produced: threshold based control, derivative based control, and clutched mechanism control. Threshold based control, as seen in Appendix G, produces actuation once a simple threshold value is reached. This is ideal for the elbow sensor, as it is easy to produce very big bend in the sensor. Derivative based control, as seen in Appendix G, produces actuation by looking at the rate of change in the resistance value. This is ideal for the shoulder sensor, where small motions can be produced very quickly. Derivative based control also has two benefits over threshold based control; derivative based control avoids any problems that might arise in a drift of resistance values over time, and it reduces the signal noise

created from walking around or other daily motions. This comparison can be seen in Fig. 47.
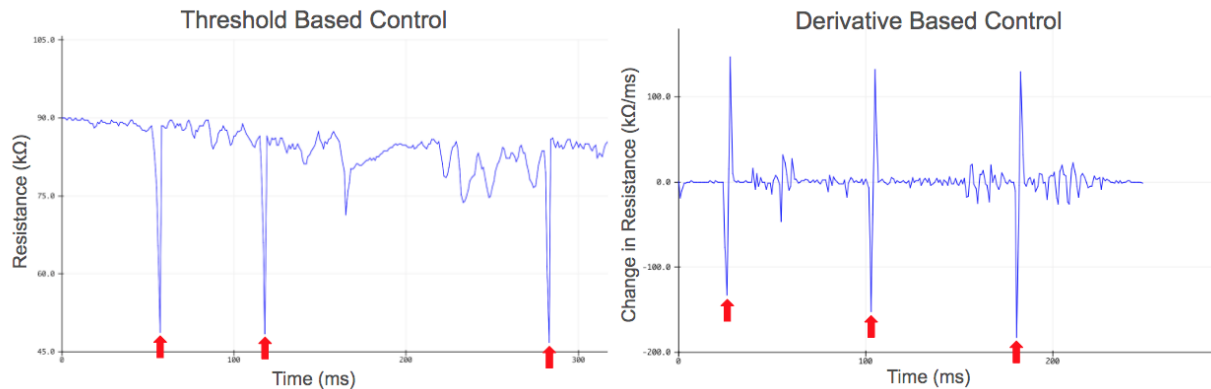
Fig. 47: Threshold based control vs derivative based control, with red arrows indication actuation points

Finally, the clutched control mechanism incorporates both derivative based control and threshold based control. When using clutch control, one large motion triggers the activation of another, more sensitive, sensor. For example, one big elbow movement would turn "on" the shoulder sensor, and the shoulder sensor would be active until another big elbow movement turned it "off". Clutched control is ideal for situations in which sensitive control is needed only for short periods of time; it provides the benefit of sensitive control without the potential for a lot of false triggers.

5.5 Final Design Description

The final biointerface design is composed of one long sleeve compression shirt that has small rectangular velcro patches. These patches are placed strategically to allow for sensor pockets to be attached across the top of the shoulder, in between shoulder blades, and in the crease of the elbow. The sensor pockets are only attached to the shirt at the ends of the pockets, allowing space for the sensor to bend in between the two attached points.

Once the sensor is placed in the pocket and attached to the shirt, the wires connecting the sensor to the protoboard must be looped through support loops sewn into the shirt. These loops must be as tightly sewn as possible, while still allowing the sensor to slide in and out. The loops are important in securing the sensor to the shirt and preventing it from falling out of the pocket. The sensor wires themselves are attached to quick connects at the wrist, allowing them to be quickly removed from the prosthesis for free movement.

5.6 Design Drawings

Sensor pockets were sewn out of cotton fabric to fit the flex sensors. Additionally, velcro was applied to the flex sensor pockets and the pockets were placed on the undergarment to match velcro position on the shirt. As shown in Fig. 48, each pocket was made from one piece of fabric, which was folded over and sewn to create a pocket. The inner seam line, as shown with a dashed line, was create to hold the flex sensor tightly while allowing for more velcro to be attached beyond the flex sensor width. This allows for increased stability and adherence to the long sleeve undergarment.
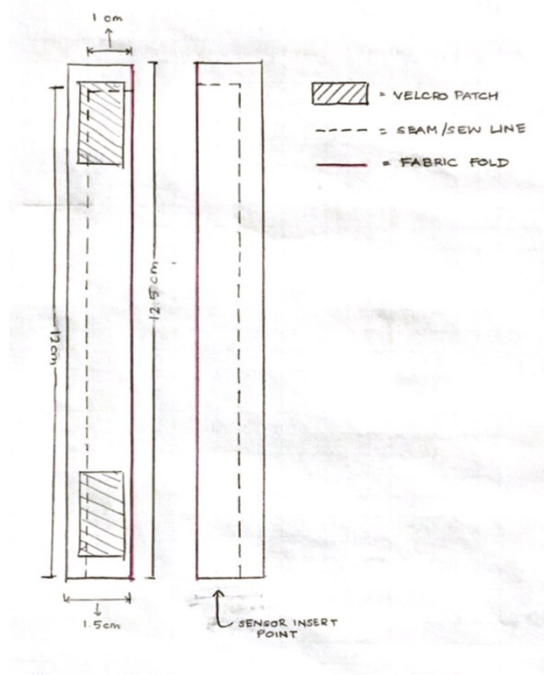
Fig. 48: Front and back schematics of sensor pocket design, to be made out of cotton fabric

5.7 Performance Verification

The first test of performance verification was conducted to see how the flex sensors responded to constant flexing over a long period of time. Although the sensors are rated for over a million cycles, there was no data on sensor drift. A test was set up using a servo motor to simply bend the sensor. It was found that while there was a small drift in resistance values, the standard deviation was less than 1% of the maximum resistance value.
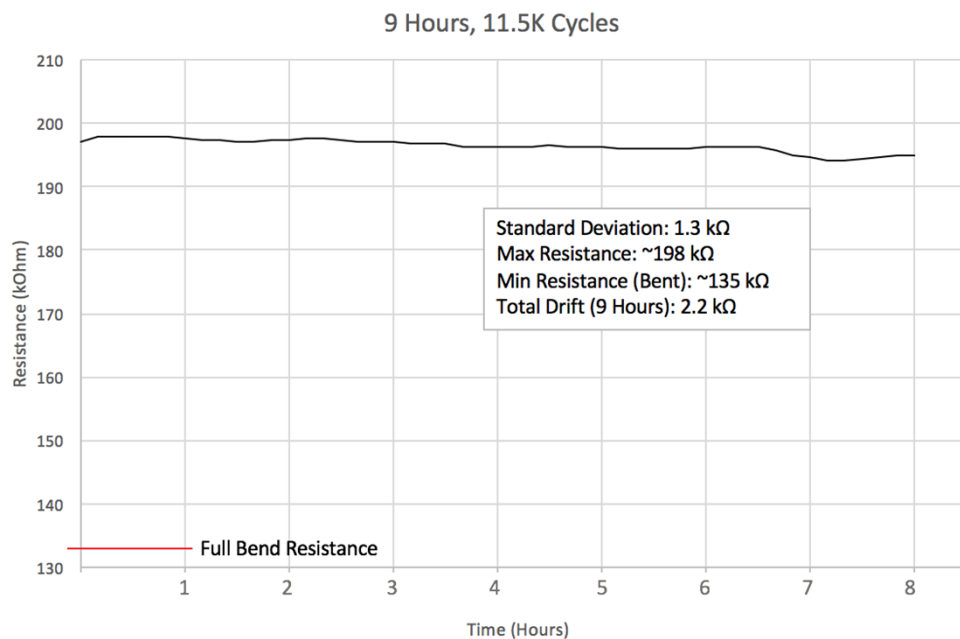
Fig. 49: Cycle testing of the flex sensors over a period of nine hours and 11,500 bend cycles

While extensive reliability testing was not conducted by this team, it will be the responsibility of future teams to conduct rigorous reliability testing to verify the function of the prosthesis. A Neyman-Pearson analysis of hand function can be conducted to verify the specificity and sensitivity of the device, which can then be used to calculate positive predictive value. For this device to be successful, a positive predictive value of above 0.95 would indicate an acceptable reliability metric. Theoretical calculations, as set up for future teams, are seen in Table 14.

Table 14. Theoretical Neyman-Pearson analysis table

	Positive User Intention	Negative User Intention
Physical Actuation	True Positive	False Positive
No Physical Actuation	False Negative	True Negative

[1] Positive Predictive Value = (True Positive)/(True Positive + True Negative)

Chapter 6: Actuation Subsystem

6.1 Introduction and Requirements

The actuation mechanism was responsible for translating input from the biointerface into physical motion of the device. It connected the electrical system to the motion of the hand by providing a physical connection between the motor shaft and the fingers.

In designing the actuation mechanism, the requirements were as follows: the actuation mechanism must support high performance metrics such as pinch force, size and weight, and anthropomorphism of movement as well as high hand robustness, feasibility, and manufacturability. These criteria address customer needs 1.1, 1.2, 1.3, 3.1, 3.3, 4.1, and 4.2 as well as the resulting product specifications for grip force, total mass of the hand, total cycles to failure, total volume, required maintenance period, compressive strength, and number of actuators.

6.2 Options and Tradeoffs

Given the compliant tendon and pulley mechanism decided upon at the system level, the actuation mechanism subsystem options consisted of a couple of variations on the pulley system.

6.2.1 Tracked Pulley Mechanism

In a tracked pulley system, the pulleys are restricted in movement by their attachment to a single track as shown in Fig. 50. They can therefore slide freely along only the track.
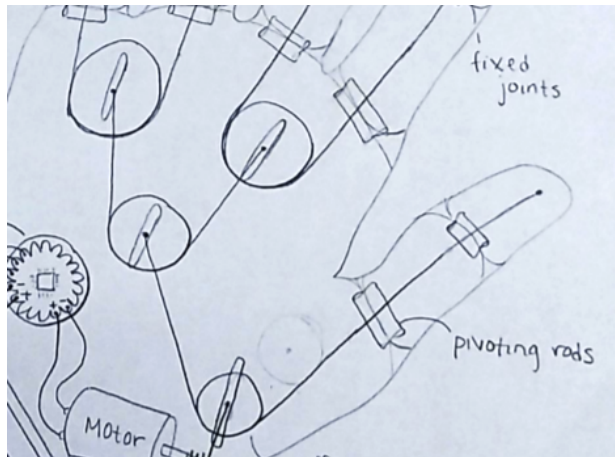
Fig. 50: Tracked pulley mechanism diagram

A primary benefit of this design is that the pulley movement is predictable and takes limited space. The pulleys are also secured directly to a backing, so no further containment is required. Finally, springs can be placed so that they pull the pulleys down in order to assure that the tendons are always under tension and will not escape the pulley wheel.

However, the tracking of the pulleys also introduces more components and detail to the design, increasing cost and manufacture complexity. The tracks for the pulleys also must be designed to allow for the necessary tendon movement. Finally, all tendons must be tied precisely as to complete the expected relationship between the movement of each tracked pulley.

6.2.2 Floating Pulley Mechanism

In our floating pulley system, the pulleys float freely between two plates such that they can move freely within plane but cannot rotate out of plane. A bracket is also placed around the pulley wheel such that the fishing line tendon can slide through the pulley but cannot fall off of the wheel (see Fig. 51).
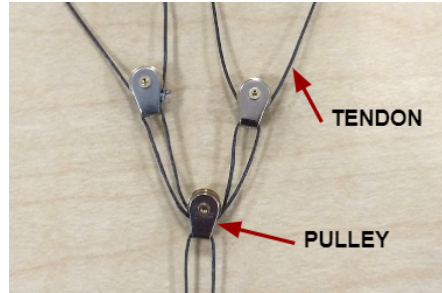
Fig. 51: Floating pulley mechanism diagram

A primary benefit of the floating pulley mechanism is that it requires fewer components than the tracked system, making it cheaper and easier to manufacture. Furthermore, the placement of each pulley and connection through the tendons requires less precision, making assembly easier. Finally, it requires placement between only two flat plates rather than attachment to a machines tracking plate, further simplifying manufacturing.

6.3 Initial Design Description

Due to the increased simplicity and manufacturability of the floating pulley mechanism over the tracked pulley mechanism, the floating pulley mechanism was chosen for the original design. The original design (shown in Fig. 51) consisted of three pulleys connected soas to translate a single pulling motion into the compliant movement of four fingers.

6.4 Prototyping Results

The floating pulley mechanism was first tested in a simple cardboard prototype as shown in Fig. 52. This demonstrated the successful compliant actuation of all fingers. This solidified our chosen design mechanism.

Fig. 52: Cardboard prototype achieving compliance

Through the next iterations, the palm, fingers, and electronics were produced in more robust materials, and they slowly evolved towards their final form. Once all components were integrated into a single device, it was noted that the system was too large to fit into a prosthetic glove and that the actuation was too weak to actuate against the prosthetic glove. The device was therefore narrowed to be the width of 3 rather than 4 fingers, and two sets of fingers were selected for actuation. The actuation mechanism was therefore simplified to contain only one pulley, allowing for twice the force to be applied to each finger.
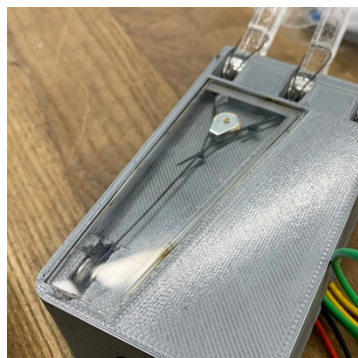
Fig. 53: 3 finger actuation mechanism

Once the device was running inside the glove and therefore be placed under the expected stresses, it was seen that the pulley knots were the first point of failure in the pulley mechanism. The sliding of the knot would allow for the unintended release of the

fingers. Many approaches of securing the line were therefore tried (different knot types, multiple adhesives, and even metal crimps) with the goal of finding a secure and precise method of fastening the line which was also easy and fast to perform. Ultimately, the double fisherman's knot was selected as the most secure knot that can be tied quickly and precisely. In order for the double fisherman's knot to be effective, the tendons were looped through the pulleys entirely such that the line was doubled back on itself (see Fig. A-1).

6.5 Final Design Description

In the final design, a single pulley translates the pulling of the bottom tendon into the underactuated motion of two sets of fingers. The fishing line tendons are looped around the pulleys and are tied using double fisherman's knots.

6.6 Detailed Design Drawings

All components of the floating pulley system were off-the-shelf parts. Fig. A-1 in the appendix shows the completed sub assembly including the approximate fishing line lengths. The line should be tied to fit the proper finger angles and then trimmed, as described in Chapter 11: Path to Production. Fig. A-2 in the appendix shows the modification of the pulley to remove the wire hook.

6.7 Performance Verification

6.7.1 Pulley Strength Analysis

Because the pulleys used in the design were originally intended to be model ship pulleys, they were identified as a potential source of mechanical failure in the design. The pulleys are made of brass and are very small and thin, making them a potential weak point. This analysis is intended to address the concern of the pulley's structural integrity, particularly with respect to the shear in the bolt that keeps the pulley assembly together.

Operating Assumptions: The pulleys were assumed to be loaded such that all forces were vertical with respect to its vertical axis.
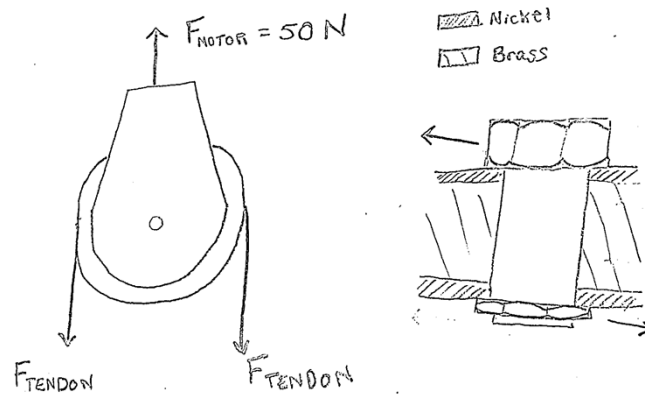
Fig 54. Free body diagram of pulley & bolted joint

Materials: The pulley wheel and the central bolt are made from brass. The pulley block is made from nickel.

Loading: For the sake of the FEA model, the top face of the pulley block and the bolt were assumed to be fixed. A 50 N force was applied pulling straight down on the pulley. In actuality, this 50 N would be split between 2 linear forces from the tendons. The 50 N pulled on the pulley imply that the fixation of the block will pull back with an equal and opposite force, and the bolt will take some of that load as well.

Hand Calculation: Hand calculations for shear and bearing stresses in the bolt are shown in Fig. 55.

Fig. 55: Hand calculations for stress in pulley

<u>Finite Element Results:</u> FEA results are shown in Fig. 56.
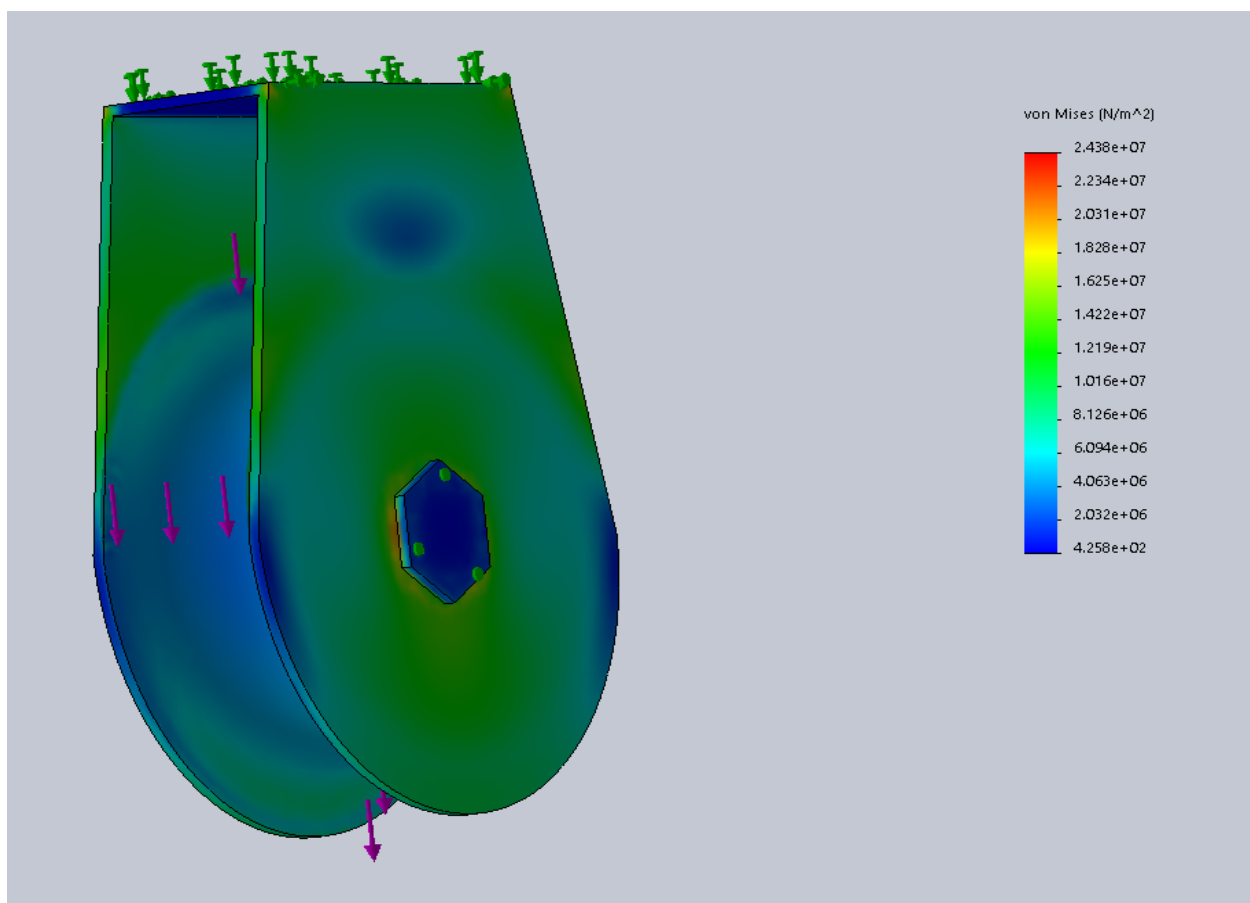
Fig. 56: FEA results on pulley

The peak stresses in the pulley were found at the bolt and at the corners of the pulley block. The bolt, presumed to be made of brass, is at the most critical stress relative to material strength at 24 MPa. The yield shear strength of brass is 77.9 MPa. The FEA

80

suggests a factor of safety of approximately 3.2, suggesting the pulley is not expected to fail at a load of 50 N.

The hand calculations suggest that the bolt will experience 15.9 MPa of shear stress, which is just shy of the 24 MPa Von Mises stress expected in that area, again suggesting that the pulley should be safe from failure.

The pulleys are therefore not expected to be a point of concern for failure in the design. Due to the relatively low forces that the motor is capable of providing, the maximum force on the pulleys should not result in shearing of the bolt.

This was further verified through hand testing. By tying the pulley system as it is found in the palm, affixing one end to a wall, and pulling on the other end with a hand scale, the point of failure was identified to be the cutting of the line by exposure of a sharp edge during the tearing of the middle of the bracket. This occurred at 39 lbf of applied tension, yielding a factor of safety of approximately 4.

It is recommended that in the future, the Mach 1 from the BioEngineering Department is used to perform tensile testing for fatigue and yield strength.

6.7.2 Tendon Strength Analysis

Because the Mach 1 was unavailable, a preliminary by-hand strength test was performed on the fishing line tendons. Through the same hand test referenced in the pulley strength analysis, the fishing line was shown to first fail through the cutting of the line by exposure of a sharp edge during failure of the pulley. This occurred at 39 lbf of applied tension.

Because the maximum output of the linear actuator is 10 lbf, the tendons by sufficiently strong to withstand maximal force application. The factor of safety is approximately 4.

It is recommended that in the future, these results are verified using the Mach 1 from the BioEngineering Department. Both fatigue and yield strength tests should be performed.

Chapter 7: Fingers Subsystem

7.1 Introduction and Requirements

The forces applied through the tendon actuation mechanism must be translated through the design of the fingers to produce grasping of the object. The finger shape, material, and movement is therefore integral to the successful function and anthropomorphism of the prosthesis.

Consequently, in designing the fingers, the requirements were that the design support the anthropomorphism of the device both while static and when in motion, support the grasping of many diverse objects, and promote the prevention of object slip. The primary decision to be made in the finger design was the number of joints to be achieved.

7.2 Options and Tradeoffs

7.2.1 Single Joint Finger Design

Single joint fingers are composed of a single finger body which is rotated only at the base of the finger. A primary advantage of a single joint design is that each finger is only a single component, simplifying the design as well as future cost, manufacturing, and assembly. However, restricting compliance to only one joint also reduces the amount that the finger can shape to the object. Because maximizing contact are serves to maximize friction between the glove and the object, single joint fingers are less conducive to the reduction of object slip.

7.2.2 Two Joint Finger Design

Two joint fingers are composed of two pieces that are hinged once at the connection point to the palm and once at the midpoint of the finger such that there is rotation between what would naturally be the metacarpals and proximal phalanges and between

the proximal phalanges and intermediate phalanges. The intermediate and distal phalanges are represented by a single component such that there is no rotation.

A primary advantage of the two joint finger design is that additional compliance is achieved by allowing each finger to form around the object. This will maximize the types of objects that can be successfully grasped as well as minimizing object slip (via friction). The additional degree of movement within the finger also holds increased potential for anthropomorphic movement as it can better approximate the movement of three bone human fingers. Furthermore, the complexity of the design is mitigated through the representation of the intermediate and distal phalanges in a single component. However, the design is nevertheless more complicated than the single joint design; the additional components increase cost, design complexity, and assembly difficulty. The additional joint also increases the challenge of producing anthropomorphic movement.

7.3 Initial Design Description

Due to the paramount importance of anthropomorphism in the device as well as concern for the functionality of the device (both through diversity of objects grasped and avoidance of object slip), the two joint finger design was selected as our original design approach.

7.4 Prototyping Results

To present a proof of concept of the two finger finger design, a SolidWorks model of a tendon actuated index finger was created and 3D printed on an Ultimaker printer. Small rubber bands were attached to the top of the fingers in order to simulate the torsional springs that can be placed in the finger joints. A small servo connected to an Arduino Leonardo was used to actuate the motion. This simple model resulted in smooth, anthropomorphic motion once the cable shown in Fig. 57 was replaced with high strength fishing line. This confirmed the possibility of creating anthropomorphic movement in a two joint finger.

However, the size of the finger made it unable to move smoothly inside the prosthetic glove. Additionally, the precise shaping and tendon routing achieved in this design was capable only due to the use of 3D printing, a manufacturing method that we did not want to use in our final design due to its limited strength properties.
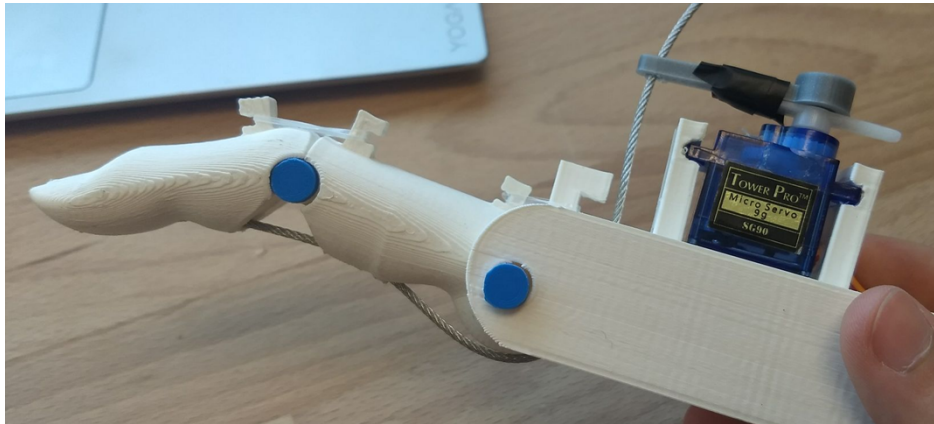
Fig. 57: 3D printed model of tendon actuated finger

The fingers were therefore produced in a slimmer form and in more robust materials as shown in Fig. 58. The finger components were laser cut out of acrylic, and Chicago screws were used to hold the joints. Torsional springs were also placed inside the finger joints such that they returned the finger to the fully extended position. Finally, the tendon was routed around the joints such that the finger contracted when the tendon was pulled upon.

When connected to a palm structure and actuation mechanism, the fingers contracted and extended as desired. However, the movement achieved was choppy and unpredictable. This was in part due to slop between the acrylic and torsional springs in the finger joints. However, the tendons also periodically slid down in between the acrylic pieces, rotating around the Chicago screw rather than the acrylic joint. This shortened the moment arm around which the tendon was transfering force, making motion difficult.

Fig. 58: 2 joint acrylic finger

From this prototype, we realized that achieving anthropomorphic motion in two joint fingers would be much more difficult than expected. Therefore, in order to facilitate anthropomorphism and simplicity in the design, a switch was made to the single joint finger design. Additionally, the thumb was made to be entirely passive in order to account for the limitations of tendon routing through the palm (see Chapter 8: Palm Structure).

In the new prototype, the fingers were made of a single piece of laser cut acrylic as shown in Fig. 59.
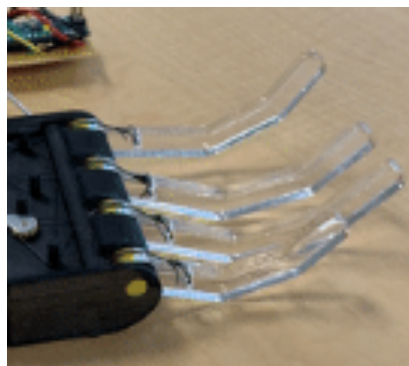
Fig. 59: Single joint acrylic fingers

When this prototype was placed in a latex glove to test its anthropomorphism, it was found that while no return mechanism was build into the finger joint, the resistance of the glove acted as an effective spring constant capable of returning the fingers to the fully extended position. This simplified the requirements of the finger design. However, it was also noted that the effective spring constant of the prosthetic glove was much higher than that of the thin latex glove. The prosthetic glove therefore presented too great a resistance to bending for the tour fingered design to overcome. The number of actuated fingers was therefore reduced to three. The index finger was allowed to rotate independently, and the middle and ring fingers were joined together using a D-shaped cut and a D-shaft.

A number of materials were then used for construction of the thumb. The thumb was made to fill out the glove so that its base could simply rest against the bottom of the palm, providing secure placement without the need for affixing that would make insertion of the device into the glove difficult. The thumb was first made with spray foam, but the foam was too soft and difficult to mold. The glove was therefore 3D scanned and a custom insert was 3D printed. Both PLA and a flexible print material were tested, and the PLA version was selected due to its superior resistance to pinch forces.

7.5 Final Design Description

The final finger design therefore consisted of three single joint fingers, with the index moving independently of the middle and ring fingers which were joined using a D-shaft. Compliant motion between two sets of fingers was therefore accomplished in a slim, simple package. The fingers will be made in 2024-T4 aluminum in order to achieve the desired strength and weight.

A 3D printed thumb was also fitted to the glove in order to resist the pinching forces applied through the fingers. It will remain plastic but may be molded or otherwise mass produced in the future. Finally, the pinky was filled with half of the foam finger insert provided with the purchase of a prosthetic glove.

7.6 Detailed Design Drawings

Detail drawings for the finger subsystem can be found in Appendix A as Fig. A-3 through Fig. A-6.

7.7 Performance Verification

The strength of the fingers and thumb were verified using both FEA and hand calculations. The finger was analyzed under both normal and side loading.

Through an analysis of a finger (produced in its final 2024-T4 aluminum material) with the maximum anticipated force of 5 lbf applied to the finger pad as shown in Fig. 60, the factor of safety was found to be 26.7. This was verified through a hand calculated factor of safety of 22.0 (see Fig. 61).
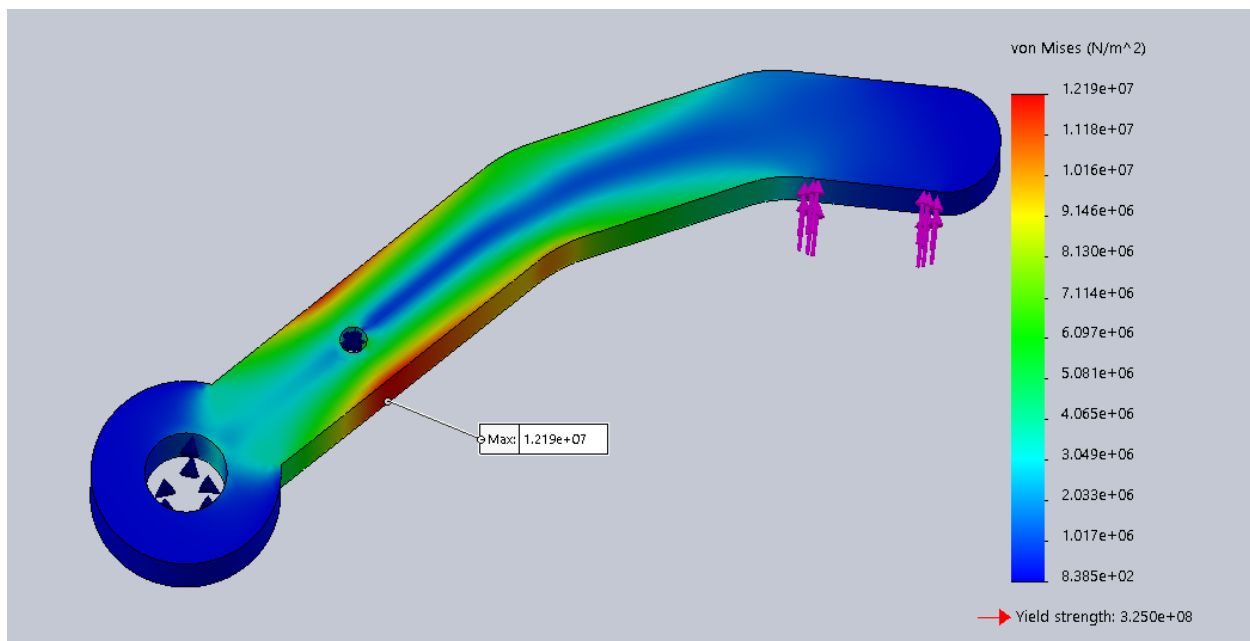
Fig. 60: FEA results on normal finger loading
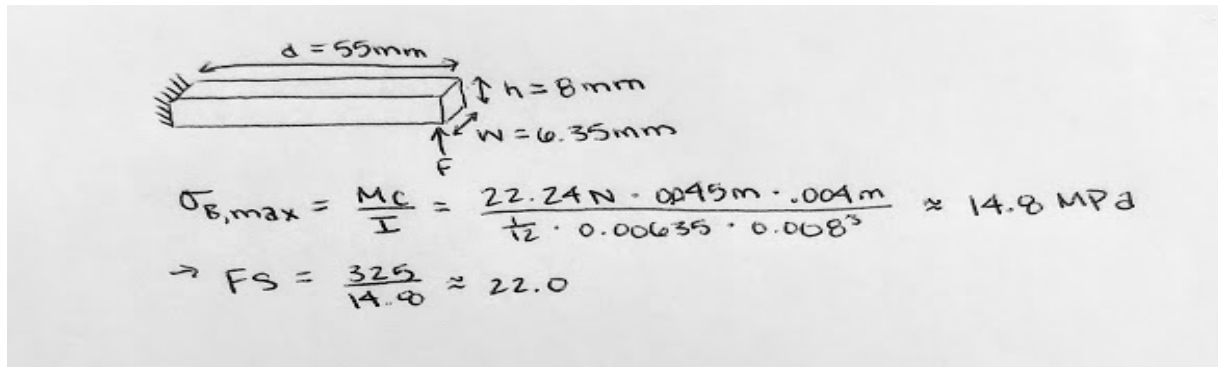
Fig. 61: Hand calculations on normal finger loading

Through an analysis of the same finger with the maximum anticipated side load of 2 lbf applied to the fingertip side as shown in Fig. 62, the factor of safety was found to be 23.9. This was verified through a hand calculated factor of safety of 43.6 (see Fig. 63).
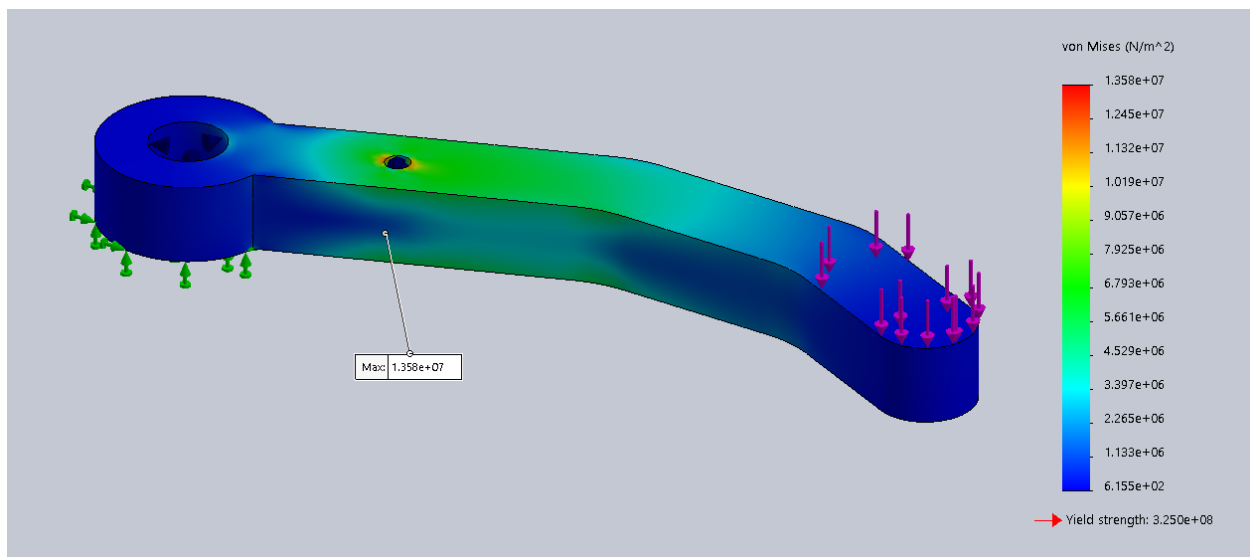
Fig. 62: FEA on side finger loading

$$\sigma_{B,max} = \frac{Mc}{I} = \frac{8.896 \cdot 0.045 - 0.003175}{\frac{1}{12} \cdot 0.00635^3 \cdot .008} \approx 7.446 \, MPa$$

$$\rightarrow FS \approx \frac{325}{7.446} \approx 43.6$$

Fig. 63: Hand calculations on side finger loading

Finally, through an analysis of an approximation of the thumb shape (produced in PLA) with the maximum anticipated force of 10 lbf applied to the finger pad as shown in Fig. 64, the factor of safety was found to be 45.9. This was verified through a hand calculated factor of safety of 59.3 (see Fig. 65).
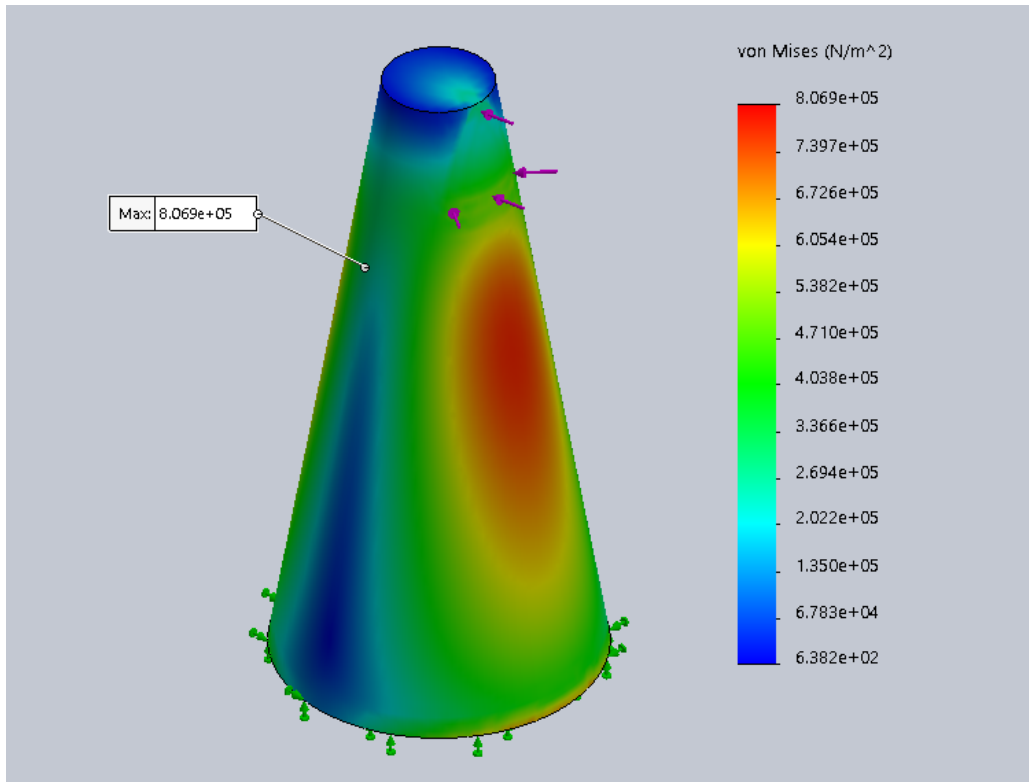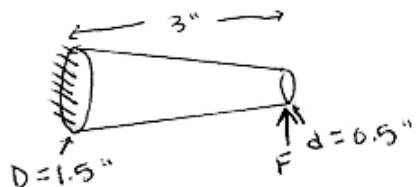
Fig. 64: FEA on thumb loading

$$\sigma_{8,max} = \frac{Mc}{I} = \frac{4448 \cdot .0762 \cdot .01905}{\frac{\pi}{64} \cdot 0.0581^4} \approx 0.6242 \text{ MPa}$$

$$FS = \frac{37}{0.6242} \approx 25. \ 59.3$$

Fig. 65: Hand calculations on thumb loading

The strength of both the fingers and thumb were therefore verified with a minimum factor of safety of 22.0. This factor of safety is high enough to place the maximum stresses in the aluminum components under the endurance limit of the material, further verifying the cycle life of the fingers.

Chapter 8: Palm Structure Subsystem

8.1 Introduction and Requirements

The palm structure is responsible for functioning as a supporting body with a central cavity that houses the motor, electronics, and actuation mechanism as well as connecting the actuation mechanism to the fingers. As such, the structural integrity of this component is critical to the robustness of the prosthesis.

In designing the palm structure, the requirements were as follows: the palm structure must support the high stress associated with high pinch force and carrying capacity, be small in size and weight, and be highly anthropomorphic once fitted with a standard prosthesis glove (see Fig. 66). These criteria address customer needs 1.1, 1.2, 1.3, 3.1, 3.3, 4.1, and 4.2 as well as the resulting product specifications for grip force, total mass of the hand, total cycles to failure, total volume, and compliant grip capability. Additionally, Chapter 6 outlines multiple design options that were being explored in parallel for the actuation mechanism. The palm structure was originally designed such that minor adjustments would allow any of the actuation mechanisms of interest to be integrated with the overall system.

Fig. 66: Prosthetic glove that the palm structure must fit within

8.2 Options And Tradeoffs

8.2.1 Exoskeletal Structure

Due to the importance of the palm structure to the anthropomorphism of the completed prosthesis design, we completed a preliminary model of an exoskeletal palm and attached fingers to assess the potential for anthropomorphism using 3D printing. The model was completed in SolidWorks and printed in ABS using an UltiMaker 3D printer. Other machining techniques would likely restrict the anthropomorphism of the structure, but within the limits of 3D printing technology, a high level of anthropomorphism was achieved as shown in Fig. 67.

Fig. 67: 3D print of exoskeletal hand model

These anthropomorphic hand models are interesting, but do not adapt well for mass manufacturability in India. These types of prosthetic hands have typically been dubbed "YouTube" hands for their wow factor but very low practicality. Problems typically

include tolerancing, durability, and actuation capability. As a result, it was determined that a more machinable and durable structure should be created. This type of structure can achieve an anthropomorphic aesthetic by fitting into a prosthetic glove, and becomes a much more practical solution to the design process. The design in Fig. 68 allows the palm structure to support and fit the actuation mechanisms discussed in Chapter 6.

8.2.2 Endoskeletal Structure

Knowing that the palm structure would be placed into a prosthetic glove from our conversations with Dr. Pooja Mukul, a preliminary model of an endoskeletal structure was also created (see Fig. 68).
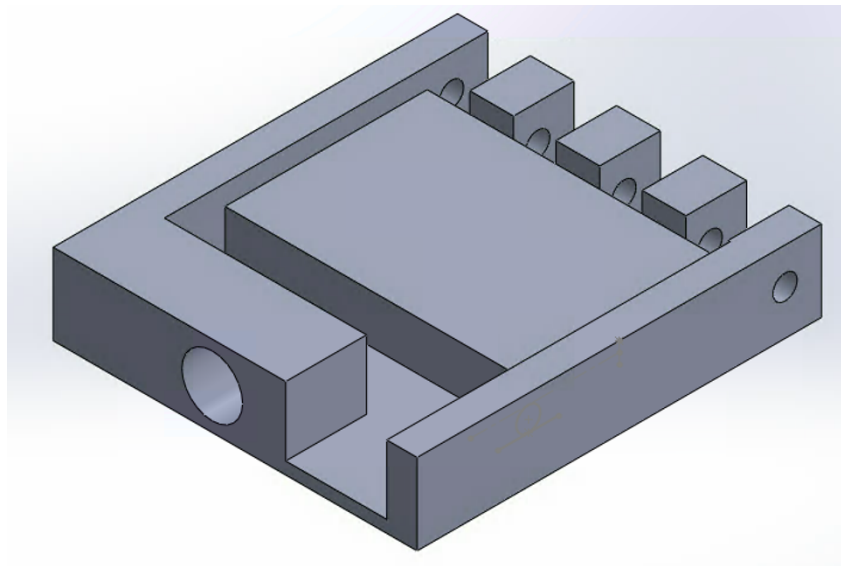
Fig. 68: 3D model of endoskeletal structure

While this type structure itself does not resemble the geometry of a human hand, its placement into a glove, if fitted properly, would allow for an anthropomorphic look. This type of endoskeletal structure still allows for all necessary components to be mounted within the palm and also greatly reduces the geometrical complexity and issue with tolerancing that typically arises with complex 3D printed parts. This endoskeletal structure has the actuation mechanism separated from it, unlike the exoskeletal system

seen in Fig. 67. This means that the actuation mechanism itself can be better tailored to the customer needs and optimized to whatever the space constraints are. This separation of subsystems also allows for easier manufacturing and maintenance as parts would be highly replicable.

In summary, this type of structure can achieve an anthropomorphic aesthetic by fitting into a prosthetic glove, and it becomes a much more practical solution to the design process. The design in Fig. 68 allows the palm structure to support and fit the actuation mechanisms discussed in Chapter 6.

8.3 Initial Design Description

With the endoskeletal structure being the clear choice for the overall framework of the palm structure, there were still two basic options to choose from: an open or closed design. An open design would mean that all the working components for the hand would be mounted to a very basic structure or spine. In other words, the structure for the open design would appear as some sort of mounting bracket that all components could be externally attached to. A closed design entails having all of the components within a cavity or set of cavities such that they could be sealed in and a part of a single overall unit. With the Indian context in mind, and knowing that sweat and dust is very prevalent for the white collar indian worker, the closed design was chosen for the potential ability to seal off the sensitive components.
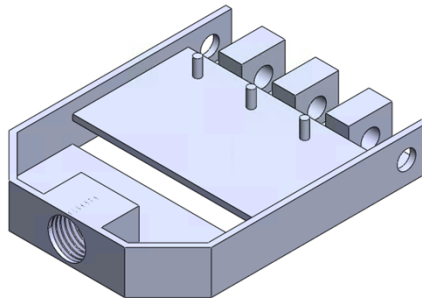
Fig. 69: 3D model of initial palm structure

Fig. 69 represents the CAD model for the initial design past the conceptual design phase. In this CAD model, one can see the attachment point for the stump, a large cavity on the top and bottom surfaces to house the actuation mechanism and electronic components, and a set of attachment slots for each of the fingers. Because this structure has a geometry similar to that of a rectangular prism with flat top and bottom surfaces, simple covers could easily be machined to cover the cavities.

The idea for this palm was that the motor could fit closely to the base of the wrist and the tendons could be routed past the alignment bearings on the upper surface (bearing to be placed on the 3 pegs to ensure the tendon is aligned with each finger) into each finger. The electronics to support the motor could then be placed on the underside of the palm in the other open cavity. With covers in place and everything secured, this structure would create a highly robust and contained system.

The palm structure in Fig. 69 was designed in SolidWorks using the basic dimensions of a human hand. The design team was not concerned with getting this initial design perfect, rather, the team was concerned with creating a prototype that would help to see how this subsystem could be optimized to support the other subsystems. In essence, the palm structure needed to be iteratively designed alongside all of the other subsystems in order for the overall project to come together in a nice single unit.

This first palm structure design was subsequently 3D printed such that it could be physically examined to determine how it would fit into the prosthetic glove and how effectively the components could fit within it. After basic initial testing, it was clear that the palm was too wide to fit within the glove: it stretched the glove and gave the wrist an unnatural rectangular shape. It was also clear, however, that the electronics and motor would not be able to fit in such a small space. Thus, it was necessary to somehow increase the size of the hand while designing it to fit better within the pre-existing prosthetic glove.

It was decided that this palm structure would be machined out of 2024 Aluminum alloy for its strength, ease of manufacturing, and relatively low cost. Originally, the design team wanted to have a final deliverable machined out of this material. Upon further evaluation of team progress throughout the senior design sequence, the team decided it would be better to continue 3D printing iterations of the palm structure with PLA and leave metal machining for future groups who could focus further on design for manufacturing.

8.4 Prototyping Results

Knowing that space optimization was going to be the primary issue for the palm structure, and knowing that other components to be interfaced with the palm would be rapidly changing, the palm structure went through a highly iterative design process. By iterating along the way, the team was able to constantly benchmark this subsystem against the overall system requirements as well as the subsystem requirements. This benchmarking process ensured that the product was being engineered directly to meet the customer's needs. The palm structure design process was highly qualitative as a result of testing for the metric of anthropomorphism. Measuring the degree of anthropomorphic appearance is highly subjective, but Dr. Pooja Mukul said that if the team could fit the device into a prosthetic glove without affecting the geometry of the glove, it would meet her criteria for anthropomorphic appearance. As for quantitative benchmarking, the weight and structural integrity of each design was monitored along the way. It was important that the palm structure contributed a weight similar to that of a humanlike hand, and also important that it could withstand a 50N force application (typical human grasp) to the structure where the fingers would be attached.

As different electronic components were added, changed, and reconfigured, the palm structure cavities needed to be adjusted to compliment the space needed. At the same time, as the finger configuration and actuation mechanism was being developed, the palm structure simultaneously needed to fully support these two other subsystems. The

overall design process became a large space optimization problem fixed with a necessity for strength and manufacturability.

The intermediate iterations began with the notes taken from the initial design (palm 1) and resulted in palm 7, the predecessor to the final design. The most difficult part of this iteration process was decreasing the width, yet increasing the height of the structure, and allowing for more internal mounting space. These intermediate palm designs are pictured in Fig. 70. With palm 7, the team had decided on a final design and simply had to refine last details for fitment and the application of acrylic covers which will be discussed with the final design.
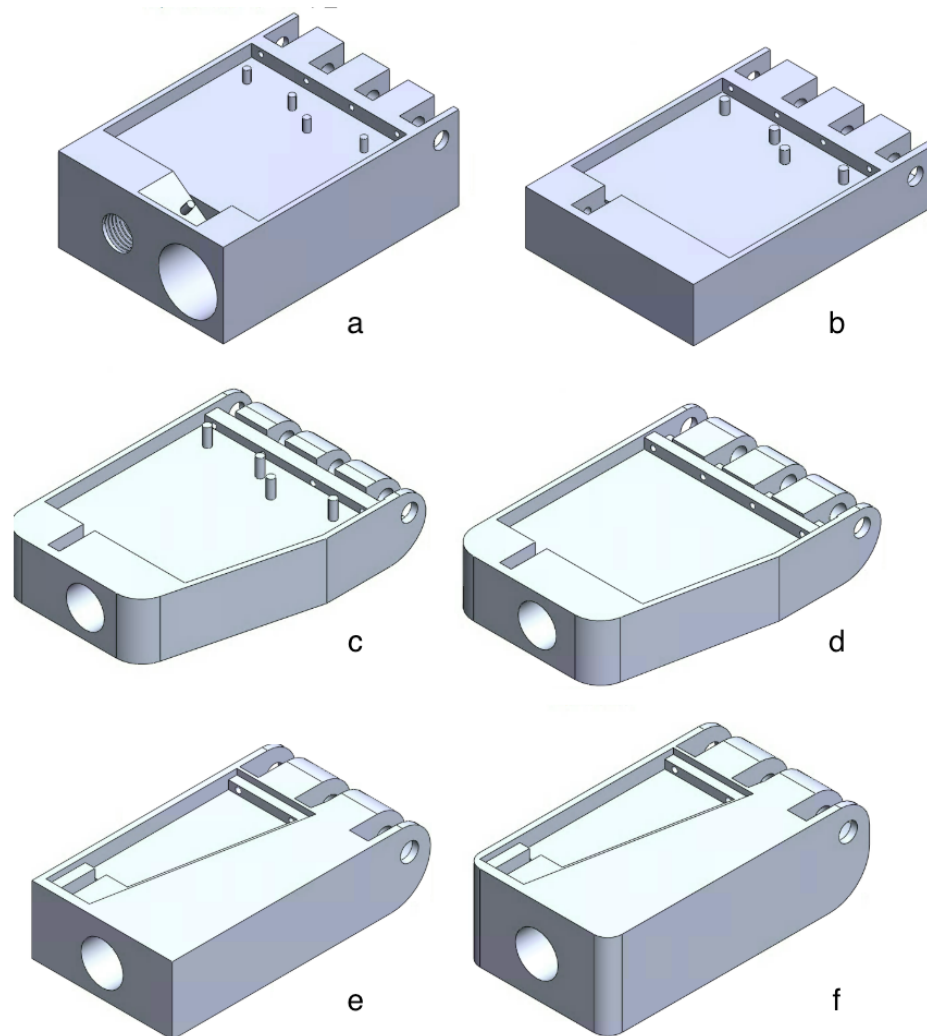
Fig. 70 a-f: CAD models of palm 2-7

The iteration process occurred over a three month period and involved a great amount of deliberation and problem resolution. The following table serves to summarize what was learned from each palm structure iteration:

Table 15: Palm structure iteration summary

Iteration	Pros	Cons
Palm 2 (Fig. 70 a)	● All components could fit within ● Tendon routing is effective	● Geometry too large to fit in glove ● DC motor cavity too large ● Can't optimize space
Palm 3 (Fig. 70 b)	● Vertical tendon routing from top to bottom surface ● Linear actuator slims down palm ● Pulleys can float freely in top cavity	● Stretches glove in an irregular manner Corners protrude from the glove ● Not enough cavity space ● Tendon routing bearing to the side actuates fingers irregularly
Palm 4 (Fig. 70 c)	● New angled geometry fits in glove much better	● Bearing alignment pegs are ineffective ● Fingers don't have enough clearance ● Fingers have trouble actuating against the glove
Palm 5 (Fig. 70 d)	● Freely floating pulleys with routing holes is simple and works ● Increased finger clearance and moment arm -> actuates against the glove better	● 4 fingers are too much to fit into the glove and comply anthropomorphically
Palm 6 (Fig. 70 e)	● 3 finger design actuates compliantly against glove ● Meets full anthropomorphism ● Acrylic cover mounting ● Routing bearing effective ● Actuation mechanism cavity space optimized	● Sharp corners ● Not enough room for electronic components
Palm 7 (Fig. 70 f)	● Room for all electronic components	● Too tall to fit in glove

Over the course of the iteration process, one can note that the cons of each design were addressed and resulted in a final design that addressed all necessary needs.

8.5 Final Design Description
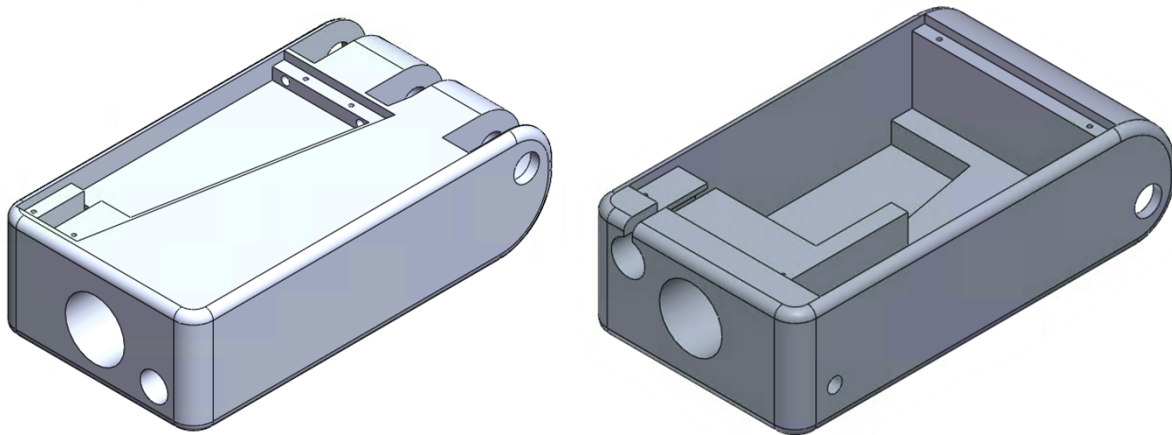
Fig. 71 a-b: CAD model of final palm structure

The final design of the palm structure was a culmination of all of the designing, prototyping, and testing that occured over the entire iterative process. In the end, the team ended with a result that met the requirements for anthropomorphism and a structure that could support the operation of all other subsystems. The main features of this final palm structure design have been outlined below:

- **Mounting fixture for stump:** The palm features a standard stump mounting configuration that is seen on other prosthetic limbs.
- **Actuation mechanism cavity:** As seen in fig. 71 a, a recessed area has been created to allow for the pulleys to freely slide with two degrees of freedom, adding to the compliant performance of this design.
- **Electronics cavity:** As seen in fig. 71 b, space has been optimized to fit the linear actuator and all required electronic components within the structure of the hand. The geometry is such that the linear actuator slides into a fixed location.

- **Electronics routing hole:** Wires from the electronics package can be guided through this hole. This allows for clean fit and finish and also ease of maintenance as the electronics can be quickly removed and replaced.
- **Tendon routing bearing:** A mounting fixture for a bearing allows for the tendon to be routed from the bottom surface to the actuation mechanism on the top surface.
- **Tendon routing holes:** Small guiding holes have been placed near the base of each finger to route the tendon in line with the finger and achieve the highest possible moment arm with this geometry.
- **Finger mounting shaft:** A 6mm D shaft runs through the tip of the palm and through the 3 fingers. This shaft allows for the fingers to move in a compliant manner. The geometry is such that the fingers are spaced anthropomorphically and slide right into each respective finger of the glove.
- **Fillets:** The outermost geometry of the palm has been designed to fit snugly into the prosthetic glove without disrupting the geometry of the glove. Sharp edges have been removed and the overall design prevents against user related injury.
- **Acrylic covers:** Both the top and bottom surfaces of the palm structure have a recessed area such that a 1/16" sheet of acrylic can be placed flush against the cavity. With this, both the actuation mechanism and electronics are sealed off from the environment.

8.6 Detailed Design Drawings

The drawings found in Appendix A, Fig. A-7 through Fig. A-12, represent the components associated with the palm structure subsystem that was designed. The Palm Structure, Palm Cover 1, and Palm Cover 2 were not derived from any pre-existing part. The Bearing Shaft and Palm Shaft are modified components from pre-existing parts.

8.7 Performance Verification

The structural integrity of this palm structure is critical to the robustness of the prosthesis, and as such a preliminary finite element analysis was conducted to evaluate the feasibility of the current prototype.

Finite Element Approximation:The loading that has been placed on the palm of the hand by the finger joints has been been identified as critical due to the fact that this will be a repeated load. Whenever the hand is actuated, and is required to hold something, the hand will be in a 'loaded' position.

This model was created to mimic the loading condition in which the hand is applying a maximum force and is under a static loading condition, meaning, the motor which supports the fingers has completely stalled and is simply keeping the fingers in position. This loading condition could be applied no matter what type of actuation mechanism is put in place into this palm structure.

The loading case was assumed to be uniform for all fingers, and thus uniform across the attachment points. While this certainly won't be the case in the actual hand, maximizing the potential load on each finger and therefore the hand allows for a more comprehensive look at the overall capability of the hand.

Simplified Free Body Diagram: Because the structure of the palm in SolidWorks has a lot of contours and irregular geometry, a simplified free body diagram proved to be much harder to create. At first, the design team modeled the palm structure as a simple rectangular beam as seen in Fig. 72. After more careful evaluation, however, the design team chose to model the palm structure as a cantilever c-beam. The simplified palm geometry and loading can be seen in Fig. 72:
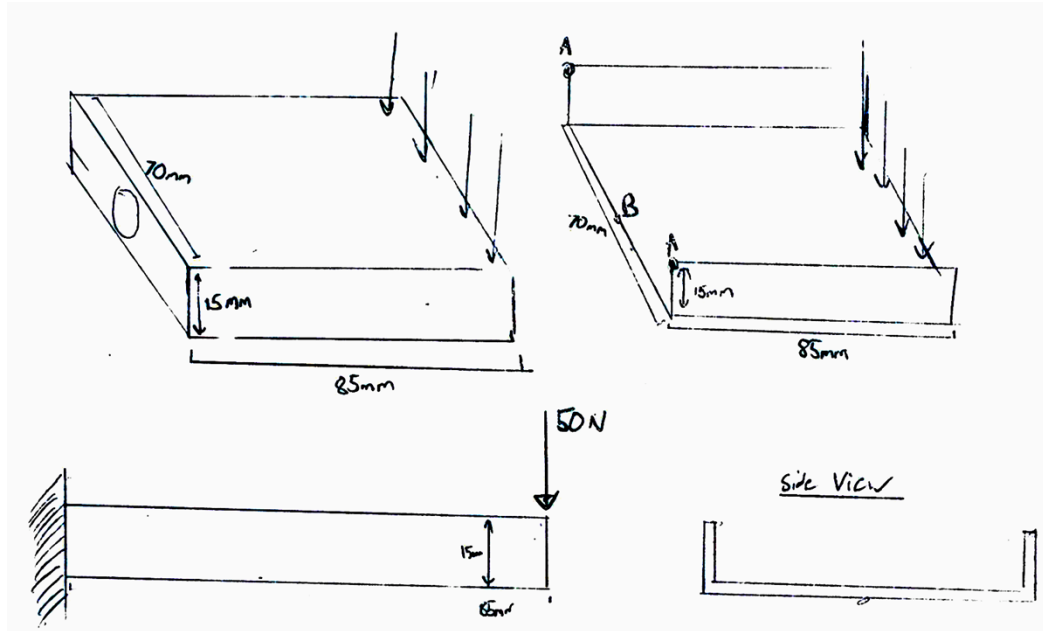
Fig. 72: Simplified free body diagram of palm structure

Material Selection: The palm was assumed to be made out of 2024-T4 Aluminum, a commonly used alloy in the aerospace industry. While slightly more expensive, this alloy is highly machinable and exhibits a superb strength to weight ratio (Young's modulus = 73 GPa , yield strength 325 MPa)[1] . It's high machinability is very attractive to our design team and allowed for a greater chance of success with our final design. Given that a primary concern of the project was cost, it is a possibility that the final palm material (once designing for manufacturability with a future team occurs) will be different. Future design teams will continue to explore material options that are highly machinable and still exhibit good strength qualities.

Loading Condition: As with most prosthetic hands, there is one main attachment point at the base of the wrist. This attachment point typically is a threaded hole that allows a stub fitting to interface with it, thus connecting the hand to a human-fitted interface. Because of the nature of this attachment point in being the basis for stability in the hand, it was modeled as a fixture as seen in Fig. 73.
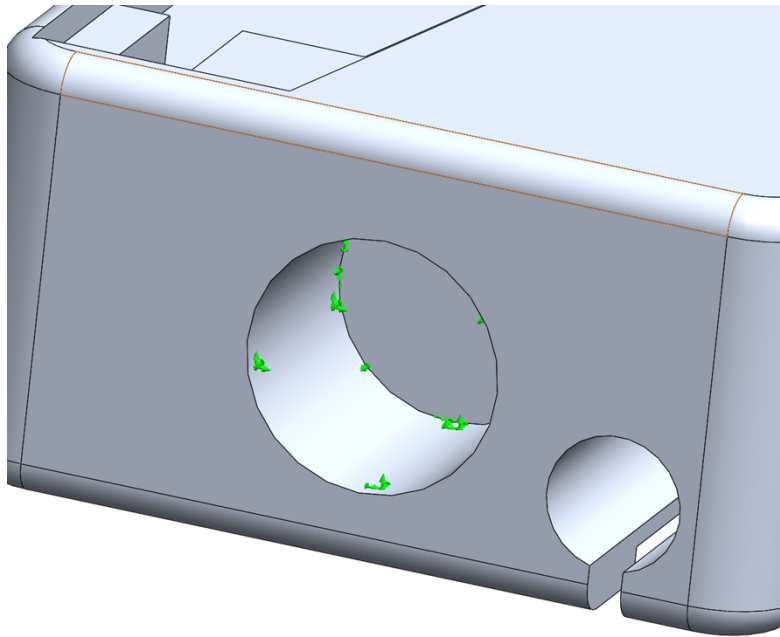
Fig. 73: Fixed attachment of palm structure
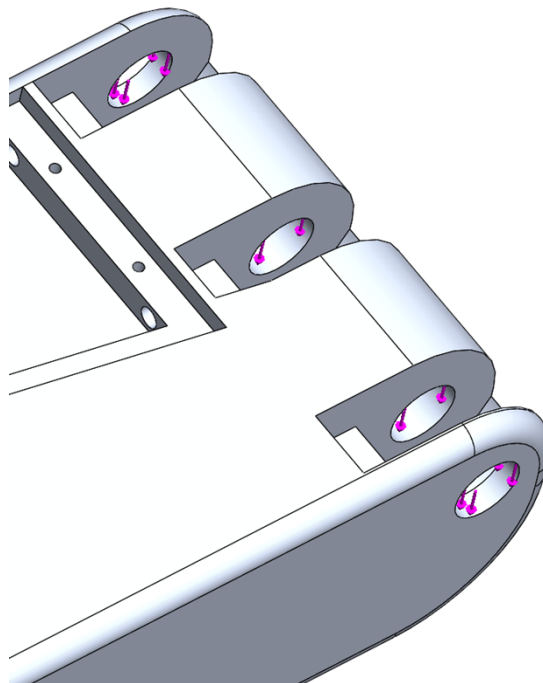
Fig. 74: Attachment and loading points of fingers

It was assumed that the finger joints are located 15mm apart from each other and because of this, each support structure is also located 15mm apart. The load is applied from the fingers to the support structures via shafts that the fingers pivot on. It was assumed that a 50N load needs to be supported by the palm, and thus these 50N were evenly distributed to each support structure as seen in Fig. 74.

Expectation of Output: While the palm was identified as a critical piece to the overall system, the design team does not expect any mode of failure to occur within it. Even though the palm is being subjected to a maximum potential load, and material use is minimal, the structural design of the palm should be sufficient to account for this and many possible other loading conditions besides the one prescribed in this study. The material used has tremendous strength capabilities and we do not expect to reach those thresholds with even our maximum loading case. We expect the palm to have higher stress concentrations in areas with irregular geometry and in locations closer to the attachment point of the wrist.

Preliminary Hand Calculations: Both bending and shear forces were assessed to be the largest contributors to stress within the palm. Both bending and shear had to be accounted for in this calculation as the simplified model was essentially a cantilever c-channel.

Two points were noted as critical in the simplified hand calculations: A. the points seen in Fig. 72 that are at the base of the palm structure but at the edge of the flanges, B. the point seen in Fig. 72 that is at the base of the palm and at the bottom flat surface.

At each of these points a thorough stress calculation was conducted that involved Mohr's circle as well as a von Mises stress reduction. The von Mises stress at each point, which accounts for the net effect of all stresses at a given location, could then be compared to the FEA calculated von Mises stresses.

At point A, it was found that the palm would experience a von Mises stress of 473.806 kPa, while at point B it was found that the palm would experience a von Mises stress of 154.510 kPa. Both of these stresses are well below the yield strength of 2024-T4 Aluminum at 325 MPa.

All hand calculations contributing to this result can be found in Fig. 75-76.
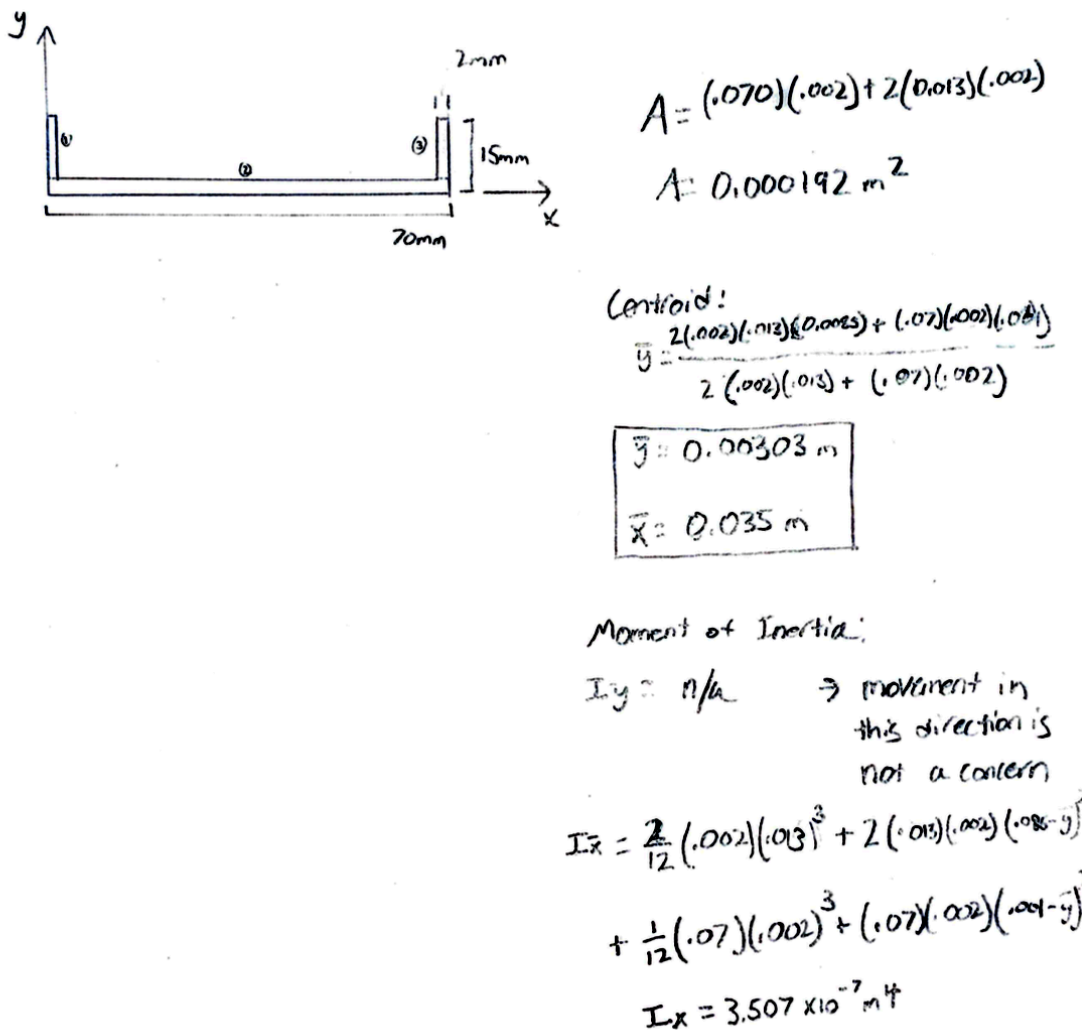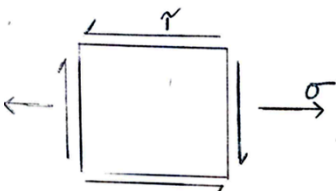
Fig. 75: Hand calculations for simplified palm structure

For point A

Shear Stress
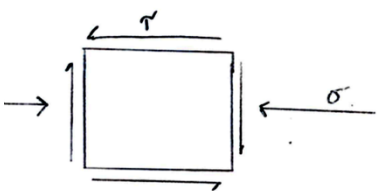
$$\tau = \frac{P}{A} = \frac{50N}{0.000192\,m^2} = 260416.7\ Pa$$

Stress due to bending (Axial)

$$\sigma = \frac{MC}{I} = \frac{(4.25N\cdot m)(0.01197)}{(3.507\times10^{-7}\,m^4)} = 145059.9\ Pa$$

$\sigma_1 = 342,858\ Pa$

$\sigma_2 = -197,798\ Pa$

Von Mises

$$= \sqrt{\sigma_1^2 - \sigma_1\sigma_2 + \sigma_2^2}$$

$$= 473,806.2\ Pa$$

For Point B

Shear Stress

$$\tau = \frac{P}{A} = \frac{50N}{0.000192\,m^2} = 260416.7\ Pa$$

Stress due to bending (Axial)

$$\sigma = \frac{MC}{I} = \frac{(4.25/m)(0.00303)}{(3.507\times10^{-7}\,m^4)} = 36,719.4\ Pa$$

$\sigma_1 = 153,825\ Pa$

$\sigma_2 = -8765\ Pa$

Von Mises

$$= \sqrt{\sigma_1^2 - \sigma_1\sigma_2 + \sigma_2^2}$$

$$= 154509.8\ Pa$$

Fig. 76: Hand calculations for simplified palm structure cont.

Modeling Results: A standard triangular mesh was applied to the palm CAD model in Solidworks. The mesh was chosen to be of moderate size and produced convergence to a change of about 0.2 MPa with changes of 0.3mm in the average mesh size. As seen in Fig. 77, the two critical points of interest were probed and the results have been displayed. Point A exhibited a von Mises stress of 6.32 MPa while point B exhibited a von Mises stress of 2.01 MPa. Both of these values are well below the yield strength of 2024-T4 Aluminum at 325 MPa.
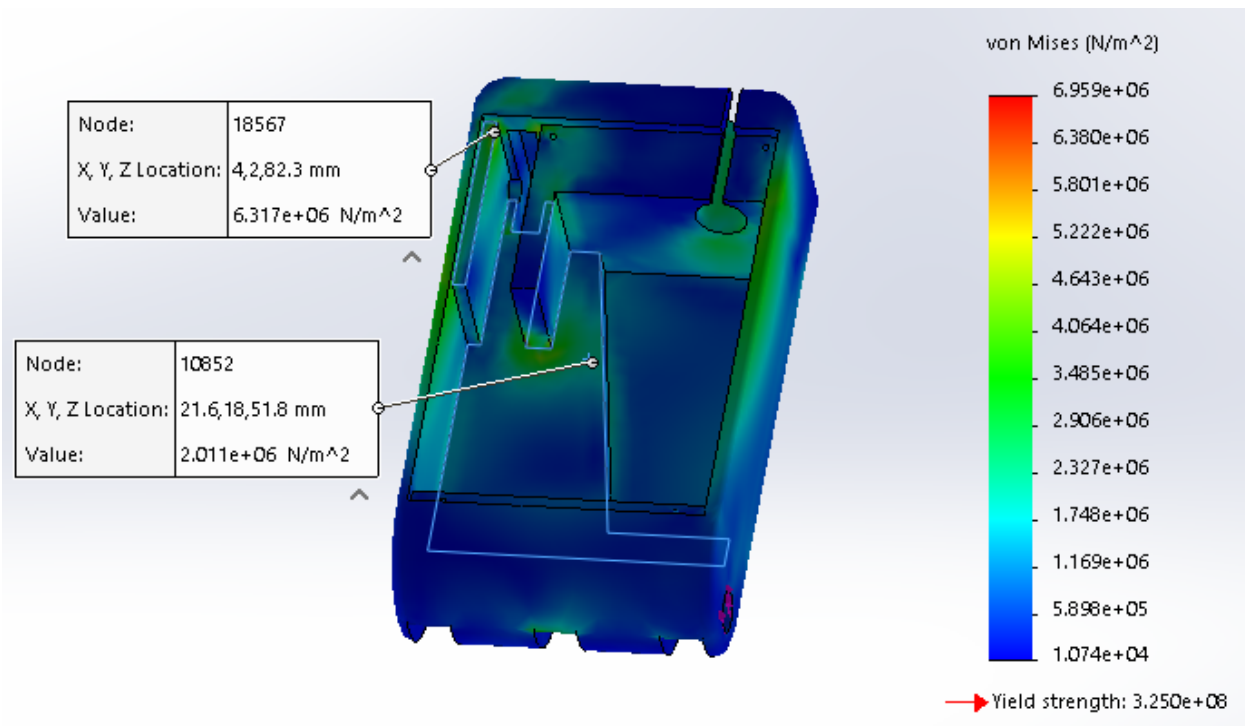
Fig. 77: FEA results for final palm structure design

Interpretation of Results: There is a clear discrepancy in the results between the hand calculations and the FEA model. At first glance, however, it can be noted that the predicted areas of concern are correct at point A and point B. This is seen with the coloration gradient in Fig. 77. Properly identifying these points and verifying them through FEA allowed the design team to focus on this point in the palm structure to ensure that no other stress concentrations are present and to look at potential solutions for minimizing this stress.

The FEA results for point A resulted in a von Mises stress 13.3 times larger than the predicted hand calculated value. The FEA results for point B resulted in a stress values 13.1 times greater. While there is about a one order of magnitude difference between the two sets of results, the study is still extremely valuable.

First, the material will not fail under this loading case, or any other similar loading case as the yield strength of 2024-T4 Aluminum is far greater than the stresses experienced by this palm. Second, the geometry used in the hand calculation and the geometry used

in the FEA model are drastically different. In order to conduct the hand calculation, the model had to be greatly simplified which removed a lot of the irregular geometry and potential for stress concentrations. Also because the FEA geometry was different, the CAD model had to be probed in slightly different locations than defined by points A & B in the hand drawn model. Thus, if we were able to more accurately represent the palm structure by hand we would expect the calculated stresses to increase by a significant degree and likely come closer to matching the modeled results.

Potential Errors: Further analysis of the FEA model and hand calculations could be performed to achieve better corroboration between the two results. Given concerns about the accuracy of the finite element solution around the base of the palm, a comparison between the FEA and hand calculated stresses could also be performed at the center of the palm where the stress gradient is small. Furthermore, it should be acknowledged that the FEA results include a margin of error as a numerical solution. However, this is mitigated by the assessment of convergence as the mesh size is changed. Improved FEA results could also be achieved by smoothing the corners of the palm where the highest stresses appear as FEA software typically has difficulty solving around sharp geometries. Alternatively, biased seeing around these corners could better around for the high geometric and stress gradients.

End to End Testing: Once the entire system was fully assembled, the team performed end-to-end testing on the design. This testing first involved loading the hand with various different objects and qualitatively analyzing how the hand reacted. The final printed palm structure, as seen in Fig. 78 , held up to the loading conditions it was subjected to and performed as expected. Given that the palm in this assembly was made out of 3D printed PLA, we would expect the palm to perform with an even higher factor of safety once made out of 2024 Al.

The team also analyzed other metrics of the hand, such as pinch force, as will be described in Chapter 10 of this report. The palm structure performed exceptionally well through all tests and allowed for the hand to meet all of the established benchmarks.
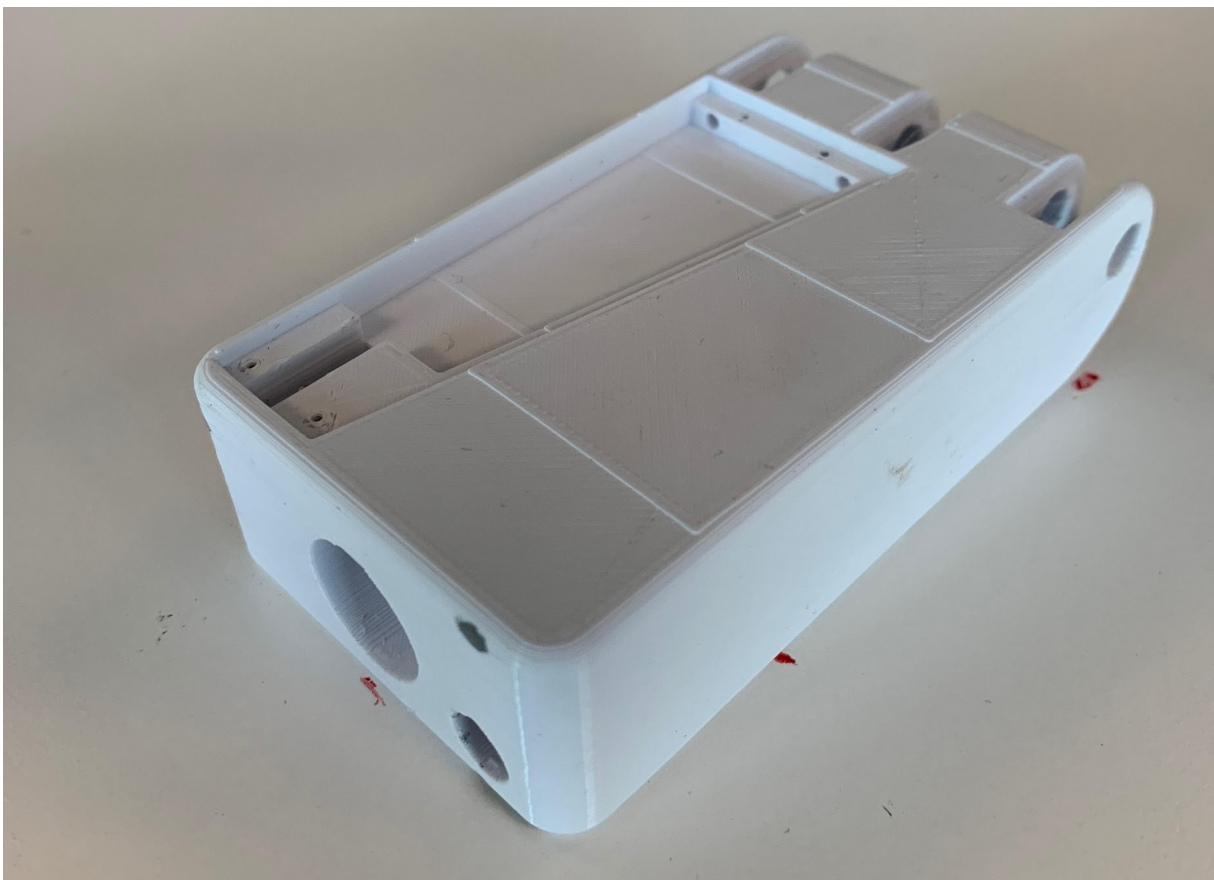
Fig. 78: Final 3D printed version of palm structure

Chapter 9: Electronics Subsystem

9.1 Introduction and Requirements

The electronics subsystem was responsible for taking a digital signal from the biointerface and then triggering actuation of the hand. A motor, power source, circuit and processor were selected in order to achieve this objective. The block diagram in Fig. 79 outlines a basic conceptual design of the system.
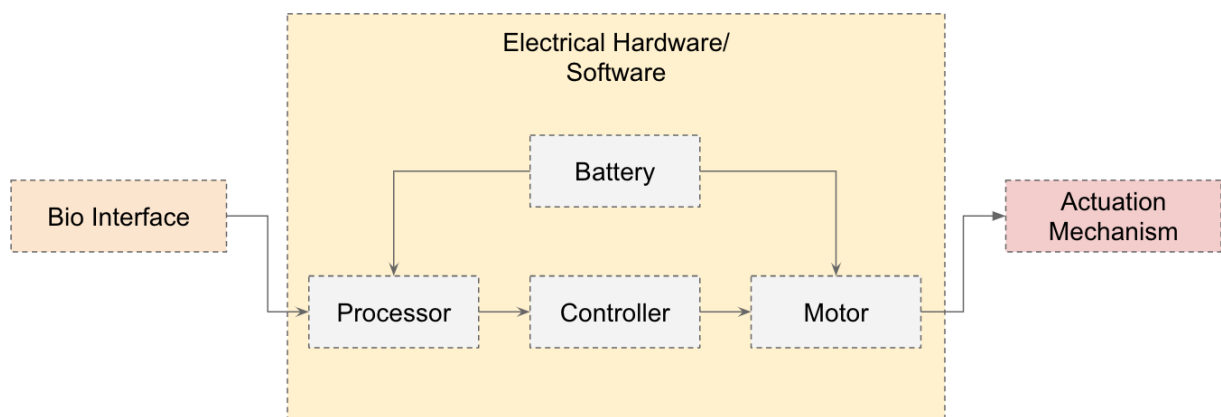
Fig. 79: Electronics subsystem conceptual block diagram

In designing the electronics, the requirements were initially stated as simply supporting the needs of the mechanical subsystem. Because the skills of the project team lie primarily in mechanical engineering and mechanical design, optimization of electronics was not seen as a priority, rather a supporting subsystem. As design choices were made on the mechanical side, more specific requirements were determined for the electronics.

The most important design requirements in this subsystem involved the motor. The motor needed to actively provide enough torque to overcome the effective resistance of a silicone-based prosthetic glove. Additionally, the motor needed to have a high backdrive torque (made possible through a built-in or external gearbox), such that objects could be held passively in place. Relying on non-backdrivability, the motor

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would run off of power only when closing. Once closed, the motor would not draw power from the battery, and hence battery life could be optimized.

Along with motor performance, motor control was also deemed crucial in achieving a successful design. Position control, such that the processor always could determine the state of the motor, was necessary in order to implement a state change biointerface.

For the battery, the guiding requirements were battery life and weight. Both an externally mounted or internally placed battery were considered initially, meaning physical size was not a particularly sensitive factor. Finding a battery that could meet the baseline battery life (8 hours of continuous actuation, see Chapter 3.2) was necessary for ensuring a user would never need to charge their prosthetic during a single day's use.

The final requirement that informed design decisions was size. The motor, circuitry and processors ideally all needed to eventually fit within the profile of the palm, so that the overall hand would be contained inside of the prosthetic glove.

Overall, the requirements were targeted at achieving the desired pinch force, battery life, response time, and anthropomorphism (fitting into a prosthetic glove) outlined in the product specifications in Section 3.2.

9.2 Options And Tradeoffs

Within the various areas of the electronics subsystems, there were a variety of different options that could potentially support the mechanical system and product specifications

9.2.1 Motor Options

The first option explored was a DC Motor. There is an enormous quantity of different DC motors available for purchase in large quantities. However, there are limited number which are sold with a built-in gear box, as many choose to gear their motors separately. Of all the DC motors assessed from a variety of different suppliers, ServoCity's 34 RPM

Econ Gear Motor had the highest torque in an acceptable size profile and price point ($15). Constrained by these limited options in our price range, and the human-centered design requirements outlined in 3.1, the motor in Fig. 80 was selected due its high torque output and high backdrive torque as the leading DC motor option.

Fig. 80: ServoCity 34 RPM Econ Gear DC motor [65]

This motor introduced a number of constraints into the design. Its large profile limited the amount of space that could be used by the actuation mechanism within the glove. Additionally, having a stall current close to 4 A, and a nominal voltage of 12 V, a reasonably large and more expensive battery would be needed to provide the voltage and current needed to the motor. All of this being said, its strength would allow for a very strong pinch force, and the nature of the DC motor allowed for spooling of the tendons around the motor shaft, which meant the draw (length over which the tendon was pulled) was unlimited.

The next motor option explored was a linear actuator (servo motor). Once again, there were a wide range of suppliers selling small linear actuators at different price ranges. Most of these motors have very low torque output. The Actuonix PQ-12 Micro Linear Actuator was found to have the best linear force and backdrive force within the size and cost restraints of the hand. This motor is pictured in Fig. 81.

Fig. 81: Actuonix PQ-12 micro linear actuator [66]

In order to find any linear actuators that were capable of supplying enough torque to overcome the prosthetic glove, the price point had to be increased. This Linear Actuator costs $70. The constraints of this device are very different than the DC motor. It has a much smaller size profile and weight which leads to versatility in how it can be used in the design. However, the overall throw of the actuator is just two centimeters, which limits the range of actuation of the hand. Also, being able to apply just 10 lbf overall, the pulley differential mechanism with four fingers divides this into just 2.5 lbf in each finger (which is then further reduced by the moment arms of the tendon).

The tradeoffs between the two options are summarized in Table 16.

Table 16: DC motor vs. linear actuator tradeoff section

	ServoCity 34 RPM Econ Gear DC Motor	Actuonix PQ-12 Micro Linear Actuator
Voltage (Nominal)	12 V	6 V
Speed	34 rpm	1 cm/s
Weight	3.35 oz	0.5 oz
Stall Current	3.85 A	380 mA
Torque/Force (Stall)	95.5 lbf-in	11 lbf
Cost	$20	$70

9.2.2 Motor Control Options

In the context of selection the DC motor, motor control presented a challenge. Three different options were explored for this approach.

Force sensitive resistors could be embedded into the fingertips of the prosthetic hand and then used to sense a certain degree of applied pressure. The motor can then know to stop moving once a certain pressure threshold is reached. The biggest problem with this approach was that additional force sensitive resistors (to the ones located at the fingertips) would have to be placed in a location such that they were under pressure when the hand is in its fully open position. Otherwise, only the closed position could be precisely pinpointed.

Current sensors could be connected in series with the DC motor to determine the amount of current being drawn through the motor. When the motor needed to provide more torque (which will happen when it comes into contact with an object) the current draw would increase, and the current sensor could then cut the motor once a threshold is reached. Once again, there was an issue with determining when the hand is in its fully open position. A sensitive enough current sensor may have been able to tell the difference between current draw when the tendon is in tension versus out of tension. This transition would happen momentarily when the DC motor unraveled the tendons enough to allow the hand to return to its open position, but then continued to rotate past this.

Motor encoders are traditionally used for tracking the position of a DC motor. With this control scheme, the position of the hand can always be known. However, with the use of motor encoders alone, there was no way of determining when the hand has come into contact with another object. Additionally, one challenge with motor encoders is they take up some space on the shaft, and going beyond the length of the shaft was unacceptable in order to have the DC motor fit within the profile of the glove.

Visuals of these three control options are shown in Fig. 82 a-c.

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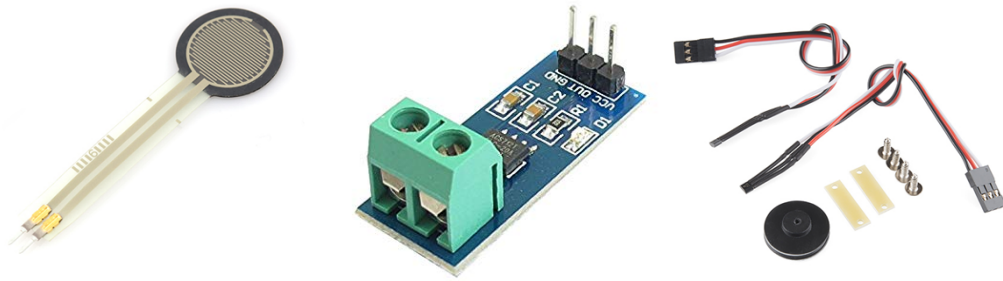
Fig. 82 (a-c) : Force sensitive resistors, current sensors and shaft encoder [67-69]

None of these motor control options were deemed capable of accomplishing the necessary control on their own, and instead, a combination of two or three options would have to be with the DC motor. All of the options are relatively low cost and simple to integrate into a circuit.

For controlling the speed and direction of the DC motor, a L298 H-Bridge chip was selected. This small integrated circuit package allows for up to 2A of current, and basic signal outputs from the microcontroller easily determine the speed and direction of the motor.

The linear actuator did not have the same control requirements as the DC motor. The linear actuator could be controlled with pulse-width modulation for simple position control, similar to any other basic servo motor. Additionally, for this reason, it did not require a motor driver.

9.2.3 Battery Options

The batteries explored were contingent upon the motor selected. The DC motor could be powered in the 6-18 V range with a nominal voltage of 12 V, and had the potential to draw nearly 4 A of current.

The first option explored for the DC motor was a rechargeable lithium polymer battery pack intended for use in RC cars (Tenergy 9.6 V 2000mAh High Capacity Battery Pack). These batteries are intended for high usage and high current draw applications. As a result, there was strong confidence that this battery could meet the needs of the hand long term, which would be useful for prototyping.

It was suspected these types of RC car batteries are not readily available in India. As a result, AA batteries were also explored as an options, as they were known to be widely available in India. An 8-pack of AA (12V) batteries has a similarly large profile to the RC car battery, and was able to provide the needed power to the motor. A 4 pack of AA batteries (6V) was also tested, but was not able to power the DC motor sufficiently.

The linear actuator could operate off of just 6V successfully, and had a substantially lower stall current (under 400 mA) than the DC motor. As a result, more compact batteries rated for lower battery life were explored. The 6 V AA battery pack was sufficient to power the motor. Additionally, a rechargeable 9V battery was explored in conjunction with the linear actuator, as it could apply the current needed, and greatly reduce the size and weight profile of the battery such that it would be a minimally invasive external mount, or could potentially even be contained within the glove.

Fig. 83 a-c shows visuals of the various battery options that were explored. The 9V and AA batteries were standard weights and sizes common to those battery types, while the RC car battery was about 9 times heavier than the 9V, two times the length and two times the width.
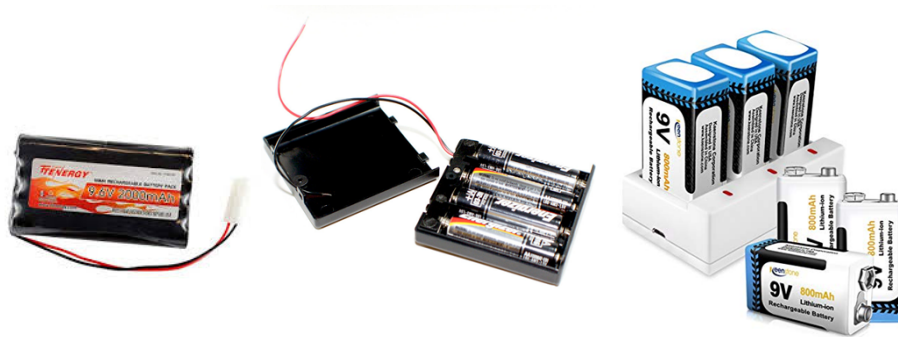
Fig. 83 (a-c): 9.6 V RC car battery, AA battery pack, 9V rechargeable battery [70-72]

9.2.4 Processor Options

For ease of prototyping and modularity of control schemes, an Arduino was selected to be appropriate for the scope of this project. Initially, an Arduino Leonardo was chosen.

Eventually, the Arduino Nano was the only Arduino product that would be able to be fully contained in the palm given size constraints. It was also useful for putting the circuit down on a protoboard given it could be mounted through hole.

The profile of the Arduino Nano is shown in Fig. 84.
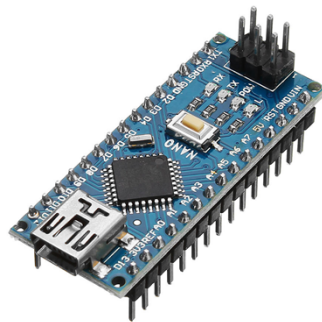
Fig. 84: Arduino Nano processor [73]

9.3 Initial Design Description

The Initial design consisted of the DC Motor, Arduino Leonardo and 9.6V Tenergy 2000mAh RC Car battery. All three motor control options (force sensitive resistors, current sensors and motor encoders) would be explored in parallel alongside this initial configuration.

9.4 Prototyping Results

The initial design prototype is shown in Fig. 85.
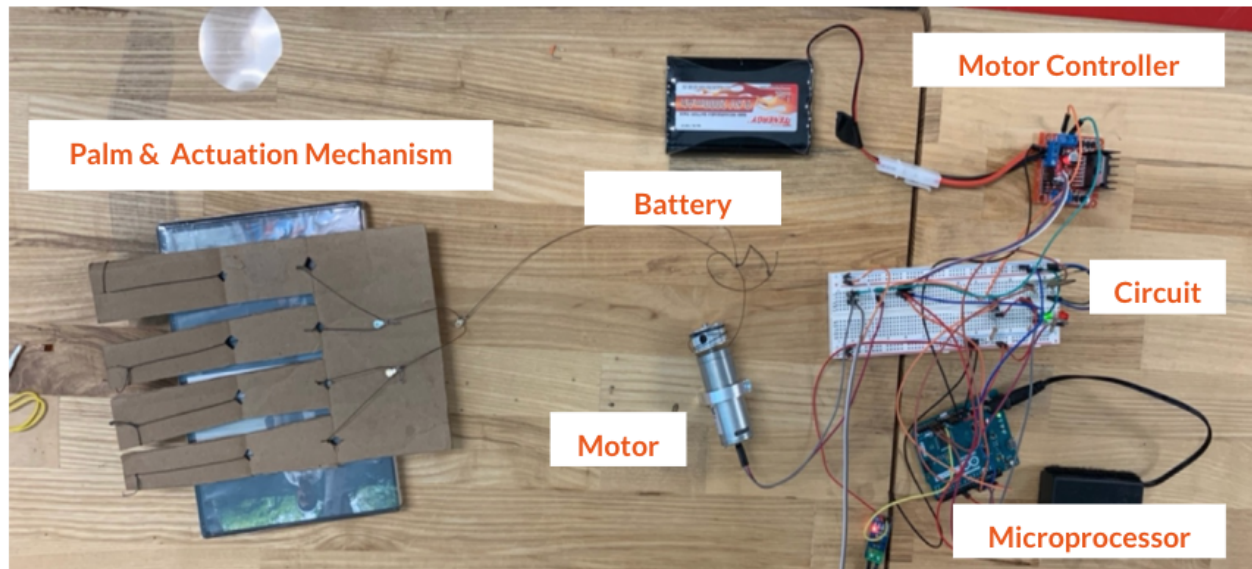
Fig. 85: Prototype of initial design

In this prototype, the motor spools the tendon as it turns, and allows the hand to actuate compliantly. For the purpose of this prototyping, the motor is manually controlled using pinches of two force sensitive resistors within the circuit. The biggest initial concern with the electronics subsystem is the size. Specifically, the motor itself is basically the entire width of the wrist, which adds complications with pulling directly downwards (not at an angle) on the tendons. From this, it was decided that the motor would be oriented length-wise in the hand, and then the tendon would be routed to pull as intended. This new palm structure concept is shown in Fig. 86.
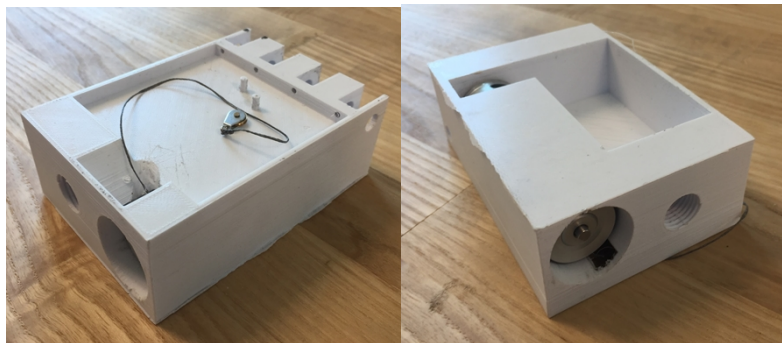
Fig. 86: Motor in-palm design

From this design, it was determined that actually fitting the DC motor into the exo-skeletal palm structure that was critical to the actuation mechanism was not particularly practical. The linear actuator would now be used instead.

With the shift to the linear actuator, the motor was more easily able to fit under the palm, and focus could be shifted to the other electronic components. At this point, the battery selection had shifted to 8 AA batteries. Now with the linear actuator, only 6 V was necessary, and the number of AA batteries was cut in half to 4. Additionally, the circuit was ready for a permanent prototype. The Arduino Nano could now be used with a protoboard to downsize the overall circuitry. Integrating with the biointerface (flex sensor), the overall profile of the electronics was greatly reduced as shown in Fig. 87.
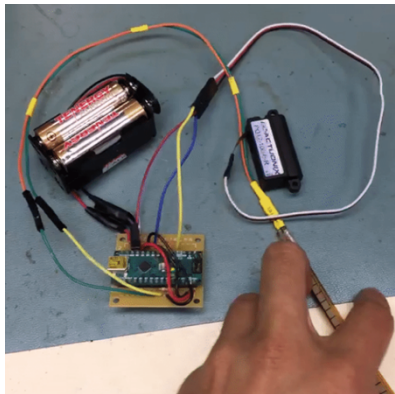
Fig. 87: Electronics mounted on protoboard

To further decrease the battery profile, and reduce waste for the user, a rechargeable 9V battery replaced the AAs. After this, all remaining prototyping efforts focused on fitting the electronic design into the palm structure. Different strategies were used to slim the profile of the electronics. A layered protoboard, pictured in Fig. 88a was the first attempt. The profile was successfully narrowed to fit into the palm's cavity, but the overall height of the circuit and processors was too high. As a result, the circuitry was simplified even further by using a two-sided protoboard (placing components on both side of the board), as shown in the right image of Fig. 88b. This allowed for the design to remain narrow enough to fit adjacent to the motor in the electronics cavity, while being restricted enough in height where the acrylic cover could successfully enclose the hand.
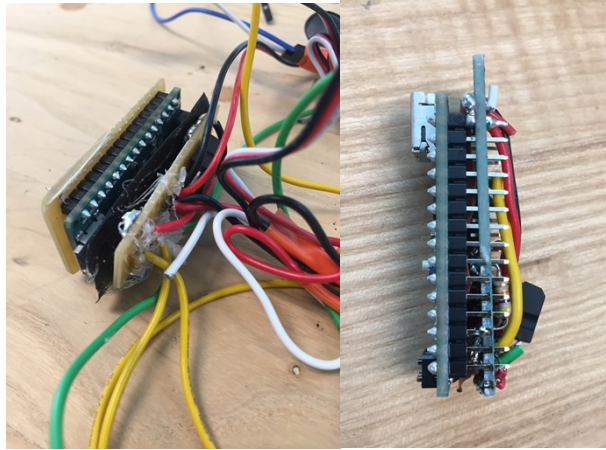
Fig. 88 (a-b): Layered protoboard, two-sided protoboard

9.5 Final Design Description

The final electronics subsystem design consisted of the linear actuator, 9V rechargeable battery and Arduino Nano microprocessor. The microcontroller and other circuitry components are housed on a two-sided protoboard that sits adjacent to the motor in the cavity underneath the palm structure, contained by the acrylic cover. A power switch and "plug-and-play" interface for the flex sensors are also added for ease of use when testing the prototype. The final design is shown in Fig. 89. The final circuitry is shown in Fig. 90.
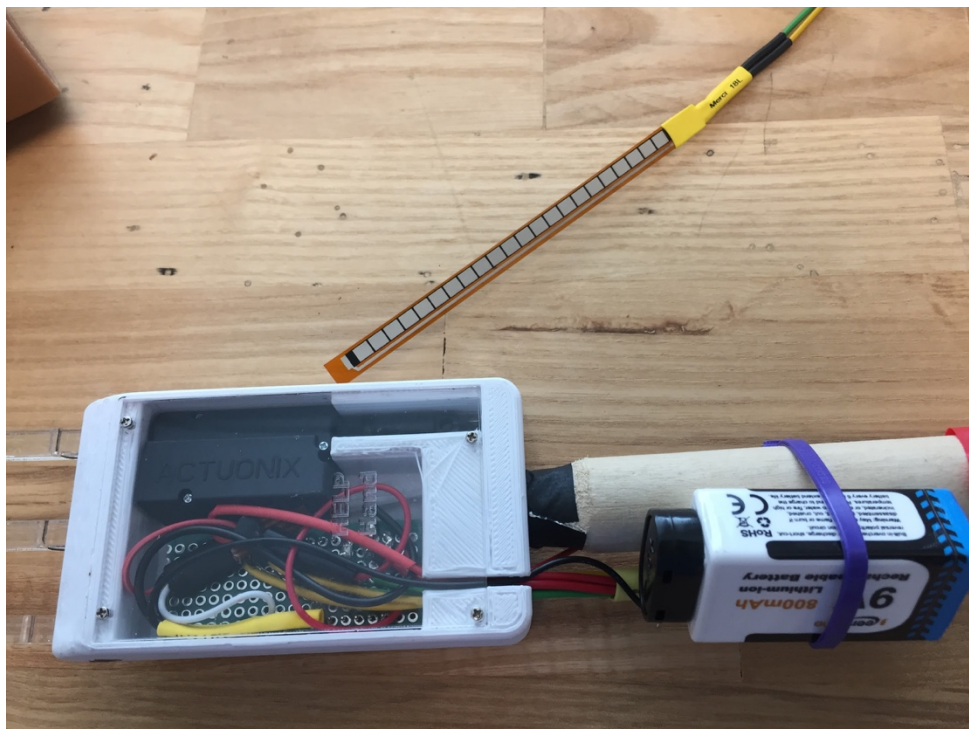
Fig. 89: Final design of electronics
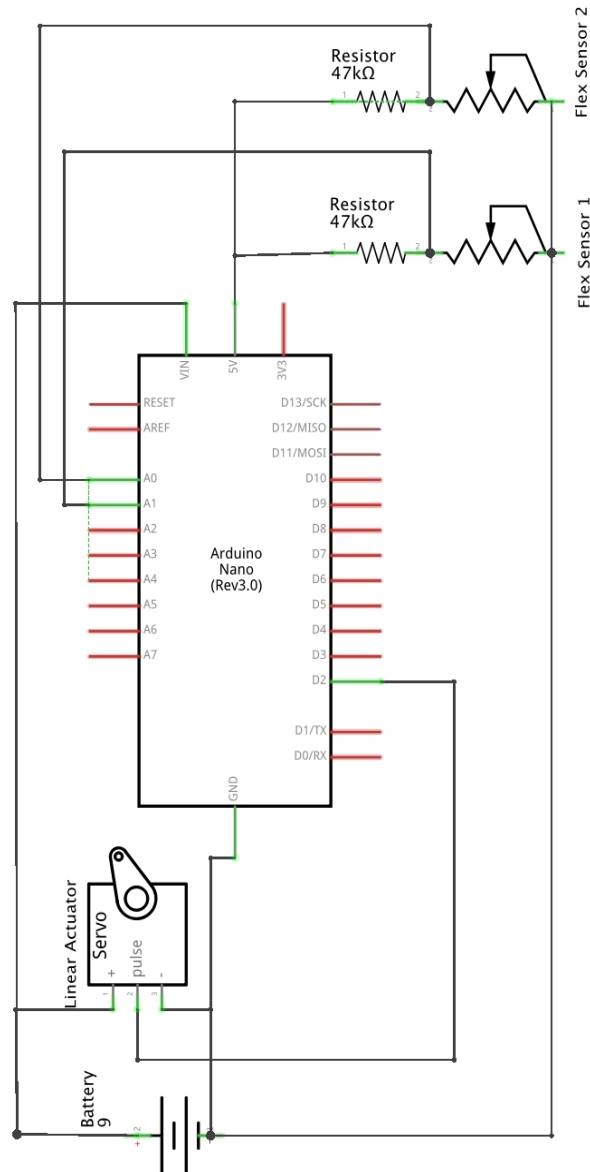
Fig. 90: Schematic of circuit diagram for final design

9.6 Detail Design Drawings

The modification made to the linear actuator for the electronics subsystem is described by Fig. A-13 found in Appendix A

9.7 Performance Verification

The linear actuator was unable to provide enough force to overcome the resistance of the prosthetic glove when the hand contained four fingers. However, when the force is more concentrated over two sets of fingers (as in the final overall design), it is strong enough. As a result, the overall electronics subsystem lived up to the objective of taking a signal from the biointerface and converting it to motion to support the needs of the actuation mechanism

The final prototyped version of the electronics did not hold up well to fatigue. Specifically, the wired connections became weaker as they were continuously cycled being bent back and forth over time. However, most of the fatigue experienced was due to constantly pulling the electronics in and out of the cavity as changes were being made. A regular user would likely never interface with their electronics. This is not seen as a serious concern, as a ready-for-market version of this hand would contain a printed circuit board.

In terms of product specifications, the electronics fit well in the palm structure (allowing for anthropomorphism through the prosthetic glove), were able to fully close the hand in under one second, and provided enough force to close the hand against the resistance of the prosthetic glove. The battery life was shown to last for 1.4 days under continuous cycling with the 9V rechargeable lithium ion battery. This is a very high use case, and suggests that the user could go long periods of time between charges.

Overall, the electronics subsystem succeeded in supporting the needs of the mechanical actuation mechanism.

Chapter 10: Systems Integration and Final Design

10.1 Iterative Design and Integration Process

As highlighted in the "Prototyping Results" subsection in each subsystem chapter, the design process for the HELP Hand was highly iterative. Beginning with a cardboard proof of concept for the compliance of the actuation mechanism, the various subsystems were consistently integrated together within physical prototypes. Fig. 91 highlights the progression of the hand over the course of this iterative process, featuring images of just a few of the prototypes that were constructed.
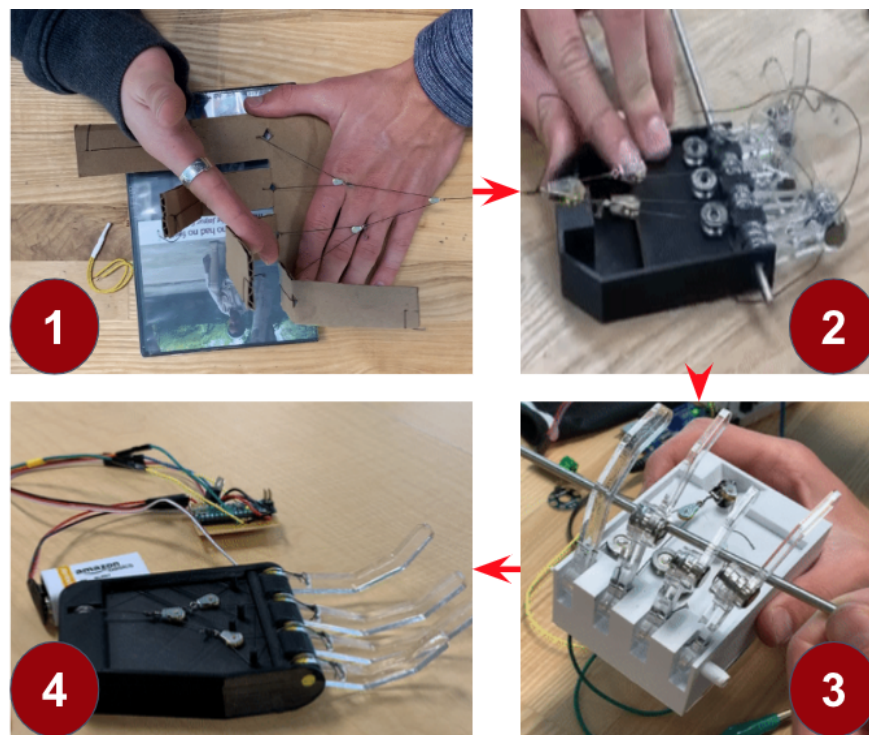
Fig. 91: Iterative prototyping of HELP Hand

In the first prototype pictured in Fig. 91, the actuation mechanism is prototyped alongside the electronics (not pictured), and the two subsystems came together. The cardboard hand achieved compliant grasps as the tendons were spooled by the motor.

The second prototype pictured in Fig. 91 brought even more of the mechanical subsystems together. Moving on from the cardboard structure, the palm and fingers were constructed from robust materials. The palm, fingers and actuation mechanism then all had to be integrated separately. The integration of these subsystems provided more challenges, and so various parts of the hand (as outlined in earlier chapters) were changed to simplify the design.

The third prototype pictured in Fig. 91 showed the result of adding in the electronics subsystem with the three mechanically oriented systems featured in the second prototype pictured. While the integration was more successful, it was clear that the design was diverging from important design criteria.

The fourth prototype in Fig. 91 is the first example where all five systems were successfully integrated. A flex sensor (not pictured) is connected to the circuit (on an external protoboard) to tell the hand when to actuate. The motor is then fitted into the palm and tied into the actuation mechanism, which connects to the fingers and results in a grasping motion.

Once full integration of all subsystems was complete, more iteration was required in order to meet the customer needs and product specifications guiding the design process. Ultimately, this iterative design process was fundamental in highlight issues on both a subsystem and overall system level, and allowing for the necessary changes to be made in order to reach compliance within the hand.

10.2 Final Design

After about fifteen weeks of continuous prototyping and iteration, a final prototype for the design of an electrically powered prosthetic hand was completed (see Fig. 92). In Fig. 92a, the hand itself is shown adjacent to the prosthetic glove that it fits into, and the flex sensor that slides into the wearable biointerface. On the right in Fig. 92b, the fully enclosed electronics are shown. The motor and protoboard are held in place by space

constraints and the screw-on acrylic cover. In Fig. 93, a front view of the wearable biointerface is shown. In this example, the sensor is attached to the inside of the elbow, one of the many modular slots where it can be placed.
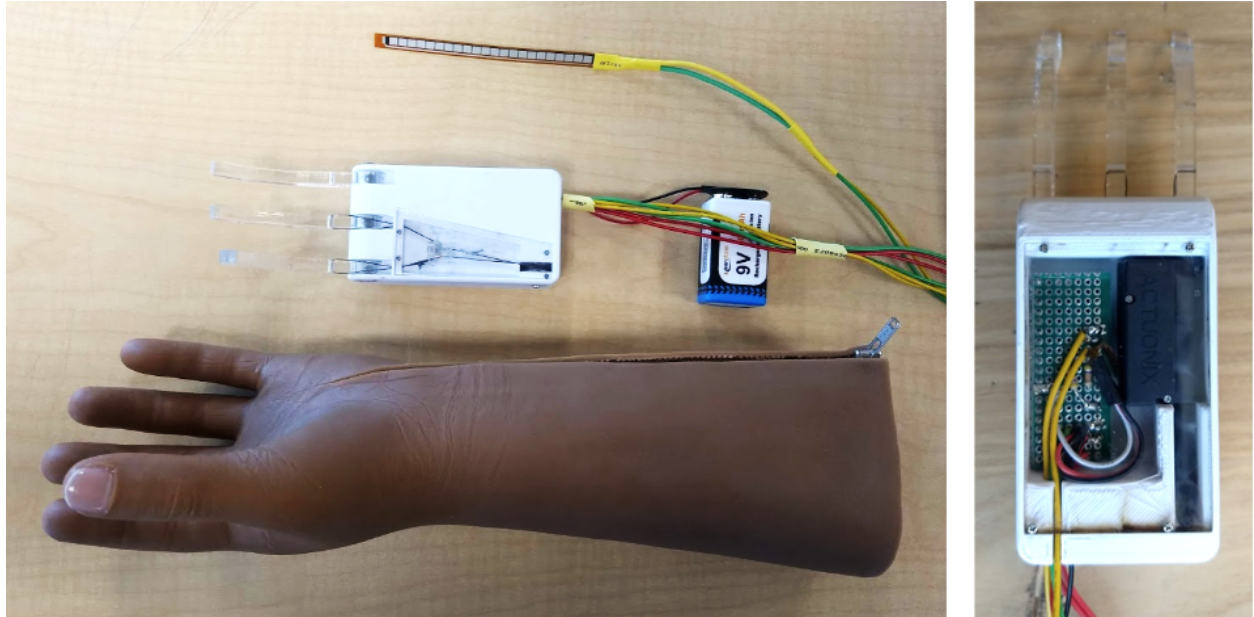
Fig. 92 (a-b): Final HELP Hand design (Mechanical/Electronics)

Fig. 93. Final wearable biointerface

The key features of the final design are highlighted below. This is a high level review of what has been outlined in the individual subsystem chapters.

3-D Printed Palm Structure. The main structure of the hand was the exoskeletal 3-D printed palm. As shown in Fig. 92, the structure contained the actuation mechanism in the palm of the hand, and the electronics in the back.

Tendon Actuation. In the design, fishing line was used to simulate tendons. These tendons were pulled on by a linear actuator, and then attached to the individual fingers. As opposed to more traditional linkage or gear-based actuation mechanisms, the tendons were very mechanically simple.

Compliance. In order to achieve a compliant grasp, a pulley was used. This serves as a force differential mechanism. When one finger hits an object and can no longer move, the other finger (or sets of fingers) attached to the pulley could still continue.

Three Fingers (Narrow Palm). In order to fit into a standard prosthetic glove, the hand could not be wider than the glove's wrist cross section. As a result, only three fingers were included in the design allowing for a narrow profile.

Single Jointed Fingers. In order to avoid mechanical disadvantage, a single jointed finger was used rather than double or triple jointed fingers that more closely mimic human anatomy.

Compliance Between "Sets" of Fingers. Overcoming the effective resistance of the prosthetic glove proved particularly challenging. The original pulley system contained three pulleys, which meant each of the four fingers were pulled by just about 2.5 lbf. By reducing to one pulley, the fingers could be pulled with 5 lbf, leading to a more concentrated force to overcome the resistance of the glove. In order to use just one pulley and still have compliance, the fingers were grouped into "sets" of fingers. The pointer finger moved independently, while the middle and ring fingers moved together. In order to do this a D-Shaft was used. The pointer finger had a circular attachment to the D-Shaft so it could rotate independently, whereas the middle and ring fingers were snugly fit to the D-Shaft such that they rotate together with it.

Enclosed Electronics In Palm. Containing the hand within the prosthetic glove was among the most important design criteria. It was desired to achieve this without having a great deal of external electronics that would have to be mounted to a person. As a result, the linear actuator servo motor, circuit and microcontroller were all housed within a cavity in the back of the hand.

Linear Actuator. A linear actuator (servo motor) was selected in order to provide the force for tendon actuation. Its lightweight, small size profile, and low voltage requirement made it an ideal choice for the application of this hand.

Modular Flex-Based Biointerface. A wearable, modular biointerface was implemented by creating a sensor that was attachable to multiple positions on a long-sleeve undergarment. This meant a user could actuate with different bodily motions such as an elbow bend or shoulder shrug.

10.2.1 Assembly Drawings

The assembly drawings in Fig. 94-95 show more specifically how the key conceptual features were implemented through hardware in the final design.

Item #	Part #	Part Name	Quantity
1	P001	Palm Structure	1
2	P002	Palm Cover 1	1
3	P003	Palm Cover 2	1
4	P004	Palm Shaft	1
5	P005	Bearing Shaft	1
6	P006	Bearing	1
7	P007	Pulley	1
8	P008	Tendons	2
9	P009	Fasteners	8
10	F001	Index Finger	1
11	F002	Middle Finger	1
12	F003	Ring Finger	1
13	E001	PQ12-R	1
14	E002-E0010	Electronics Package	1

SANTA CLARA UNIVERSITY
SENIOR DESIGN TEAM 6 : HELP Hand
TITLE:

HELP Hand Assembly

	NAME	DATE
DRAWN	Evan Misuraca	5/30/19
CHECKED	Michael Mehta	5/30/19
DESIGNED	Evan Misuraca	5/9/19

PROPRIETARY AND CONFIDENTIAL

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SIZE	PART. NO.	REV
A	HH1	A

WEIGHT: 209g (w/out electronics)
SCALE: 1:2   SHEET 1 OF 2

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
FRACTIONAL ± 1/2
ANGULAR: MACH ±1° BEND ±1°
ONE PLACE DECIMAL ±.5
TWO PLACE DECIMAL ±.05

MATERIAL:
N/A

NOTE:
Tendons not pictured

DO NOT SCALE DRAWING

Fig. 94: Final assembly drawing (1 of 2)

Item #	Part #	Part Name	Quantity
1	P001	Palm Structure	1
2	P002	Palm Cover 1	1
3	P003	Palm Cover 2	1
4	P004	Palm Shaft	1
5	P005	Bearing Shaft	1
6	P006	Bearing	1
7	P007	Pulley	1
8	P008	Tendons	2
9	P009	Fasteners	8
10	F001	Index Finger	1
11	F002	Middle Finger	1
12	F003	Ring Finger	1
13	E001	PQ12-R	1
14	E002-E0010	Electronics Package	1

	NAME	DATE
DRAWN	Evan Misuraca	5/30/19
CHECKED	Michael Mehta	5/30/19
DESIGNED	Evan Misuraca	5/9/19

SANTA CLARA UNIVERSITY
SENIOR DESIGN TEAM 6 : HELP Hand
TITLE:
HELP Hand Assembly

SIZE **A** PART. NO. HH1 REV A

SCALE: 1:2 WEIGHT: 209g (w/out electronics) SHEET 2 OF 2

Fig. 95: Final assembly drawing (2 of 2)

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10.2.2 Parts List

The parts referenced in the assembly drawings are more comprehensively defined and specified in Fig. 96.

Subsystem	Component Name	Part #	QTY	B/M/O	Vendor	Raw Cost / Unit	Raw Cost	Material (If Made)
Palm Structure	Palm Structure	P001	1	M	Undetermined	$1.42	$1.42	Aluminum
	Palm Cover 1 (Top)	P002	1	M	Undetermined	$0.07	$0.07	Acrylic
	Palm Cover 2 (Bottom)	P003	1	M	Undetermined	$0.14	$0.14	Acrylic
	Palm Shaft	P004	1	M	Amazon	$0.55	$0.55	Steel
	Bearing Shaft	P005	1	M	Amazon	$0.11	$0.11	Steel
	Bearing	P006	1	B	Amazon	$0.82	$0.82	
	Pulley (5mm)	P007	1	B	Harbor Models	$2.70	$2.70	
	Tendons	P008	1	B	Amazon	$0.01	$0.01	
	1x5 MM Screws	P009	8	B	Amazon	$0.01	$0.08	
	Subsystem Totals					**$5.82**	**$5.89**	
Fingers	Index Finger	F001	1	M	Undetermined	$0.00	$0.00	Aluminum
	Middle Finger	F002	1	M	Undetermined	$0.00	$0.00	Aluminum
	Ring Finger	F003	1	M	Undetermined	$0.00	$0.00	Aluminum
	Subsystem Totals					**$0.00**	**$0.00**	
Electronics/Sensing	PQ12-R Micro Linear Servo	E001	1	B	Actuonix	$70.00	$70.00	
	4 cm x 6 cm Protoboard	E002	1	B	Amazon	$0.33	$0.33	
	Switch	E003	1	B	Adafruit	$0.04	$0.04	
	47 kOhm Resistor	E004	1	B	Amazon	$0.04	$0.04	
	Arduino Nano	E005	1	B	Arduino	$22.00	$22.00	
	Battery Holder	E006	1	B	Amazon	$0.40	$0.40	
	9V Battery	E007	1	B	Amazon	$4.43	$4.43	
	Flex Sensor	E008	1	B	Adafruit	$24.27	$24.27	
	Wire (1ft)	E010	10	B	Amazon	$1.32	$13.20	
	Subsystem Totals					**$122.83**	**$134.71**	
Other	Prosthetic Glove	O001	1	B		$100.00	$100.00	
	Undergarmet / Shirt	O002	1	B		$20.00	$20.00	
	Battery Charger	O003	1	B		$9.95	$9.95	
Project Totals							**$270.55**	

Fig. 96: Final parts list for HELP Hand

10.3 Final Testing Results

10.3.1 Tests

Upon completion of the final design, the hand needed to be evaluated against the customer needs and specifications that had been at the start of the project. Below, the different tests that were conducted on the hand are outlined.

Battery Life Testing. The hand was continuously cycled until the fully charged rechargeable 9V battery ran out of life. Within the last few hours (as the battery was dying) reliability of actuation decreased. Altogether, the battery lasted for 1.4 days. This test validated the reliability of the hand.

Pulley and Line Strength Testing. Using a mechanical scale, load was applied to a pulley attached to tendons. From this test, it was found that around 20 lbf, the fishing line would break. The pulley was never able to be broken without the line breaking first. This test validated the durability and reliability of the actuation mechanism. Other structural integrity questions were answered through FEA.

Reliability of Biointerface. Once the wearable was created and configured, actuation was tested while moving and while sitting in a stationary position. In both cases, it was found that there were no issues with accidental actuation, and that the hand did not actuate when the user did not intend for it to actuate.

General End to End Testing. A qualitative understanding of the hand was gained by using it frequently for a wide variety of tasks. The hand was found to be very useful as a supporting limb. For example, when unzippering a backpack, the prosthetic could be used to stabilite the area around the zipper while the other hand pulled. Additionally, the hand could pick up narrow objects that would fit in the small profile of the prosthetic gloves. Objects lying flat on the table as well as larger objects were a challenge given the natural position of the prosthetic glove.

10.3.2 Analysis of Final Results

Given these tests tests, as well as other data collected on the final prototype, the design could be quantitatively compared to the initial product specifications that were desired. Table 17 provides a summary of this benchmarking comparison.

Table 17: Final design results

Customer Need	Metric	Units	Target Value	Stretch Value	Design Value
Affordability	Total Parts Cost	USD	< 400	< 250	271*
	Number of Actuators	#	1	1	1
Anthropomorphism	Total Mass	g	320 - 630	410 - 500	459
	Fits Prosthetic Glove	Y/N	Y	Y	Y
Durability & Reliability	Battery Life	days	1	3	~ 1.4
	Close Time	s	1	0.5	1
	Cycles to Failure	#	1 million	2 million	Estimated 1 million+

Anthropomorphism had been emphasized as an absolutely critical design criteria for this hand in the Indian context. The final design weight (calculated assuming a 2024 T-4 aluminum for the palm and fingers) falls in the ideal range, meaning that the HELP Hand weight mimics that of the human hand. Additionally, the overall design operates within a prosthetic glove, such that the aesthetic of the hand is highly human-like.

Durability and reliability of the hand were harder to accurately quantify giving the prototyping-nature of the project. Running tests to failure could be destructive to the team's progress within the iterative design process. That being said, the specifications that could be quantified, such as battery life and close time, met their target values. All parts that were specified for cycle life were estimated for at least a million cycles, or about three years of frequent prosthetic hand use.

The strength of the design was supported through the finite element and hand calculations discussed in the subsystem chapters; the results are summarized in Table 18. All components are expected to support the predicted use, and the fingers and thumb are predicted to have a cycle life above the device life of 1 million cycles.

Table 18: Summary of strength analyses

Component	Force Applied	FEA Factor of Safety	Calculated Factor of Safety	Conclusion?
Pulleys	50 N (~11 lbf)	3.2	4.8	✓
Palm Structure*	50 N (~11 lbf)	40.0	13.0	✓
Single Joint Finger*	5 lbf parallel to pinch	26.7	22.0	✓
Single Joint Finger*	2 lbf normal to pinch	23.9	43.6	✓
Thumb	10 lbf parallel to pinch	45.9	59.3	✓

10.4 Final Cost and Budget Analysis

10.4.1 Project Expenses

Of the $4600+ offered to the team for completion of this project, only $1,785.00 was used. The group chose to reimburse all of these funds through Santa Clara University's School of Engineering Undergraduate Programs budget. This money was used primarily for prototyping materials and spare parts. Table 19 provides a breakdown of how this money was spent across various categories of purchases.

Table 19: Categorical spending breakdown

Budget Category	Money Spent
Basic Electronic Components	$103
Bio-Interface Components	$208
Fasteners	$48
Hand Structure	$10
Motor	$335
Other Mechanical Components	$317
Power Supply	$109
Processor	$107
Prosthetic Glove	$158
Sensors	$96
Tax/S&H	$267
Testing Components	$26
Grand Total	**$1,785**

10.4.2 Cost of Final Prototype

The total materials cost to produce this prototype is $270.55. This price factors the raw material cost of the fingers and the palms if they were made from 2024-T4 aluminum. This price does not account for bulk discounting. Additionally, it does not include estimates of any manufacturing costs, which would primarily include the manufacturing of the fingers/palm in bulk, and the labor needed for assembly of each hand.

Chapter 11: Path to Production

11.1 Assembly Guide

Assembly of the current prototype should be guided by the assembly drawings detailed in Chapter 10. Additional instructions are provided below to supplement the drawings for different parts of the assembly process.

11.1.1 Tooling/Equipment Required

In order to assemble the HELP Hand in its current state, the following tools/machines were used:

Table 20: Tools/equipment required for HELP hand assembly

Tool/Equipment	Purpose
3-D Printer	Print palm structure
Laser Cutter	Cut fingers & acrylic cover
Saw	Cut shafts and motor
Cutters	Cut tendons and wires
Tweezers	Tying tendons
Super Glue	Securing tendons
Soldering Iron / Solder	Make attachments on protoboard
Wire Strippers	Connecting wires
Philips Head Screwdriver	Attach/detach acrylic cover

11.1.2 Tendon Attachment

Two seperate pieces of string are used for tendon attachment. The first piece of string is used to attach the fingers to the pulley. The way in which the tendon loops through a

finger is illustrated in Fig. 97. Then, Fig. 98 shows how the two fingers are connected to one another through the pulley, and where the piece of fishing line is tied together.

Fig. 97: Tendon attachment in finger

Fig. 98: Two fingers connected through pulley

The second piece of string is used to attach the pulley and the motor. String is looped through the hole on the end of the motor, and through the bottom of the pulley. The tendon is routed from the electronics cavity to the actuation cavity with the bearing (P006 in the assembly drawing).

When tying tendons, the appropriate tension should exist in the hand so that if the motor is fully closed, the fingers are at the position where once in the glove, the hand would be fully closed.

As shown in Fig. 97 - 98, tendons are tied in two places. This connection is done using a double fisherman's knot to connect the two ends of one piece of line together. Fig. 99 details the procedure for tying a double fisherman's knot. It is critical that the knot is tied tightly as the knots tend to be the point of failure in the hand. Superglue can also be applied over the knot to add more strength.
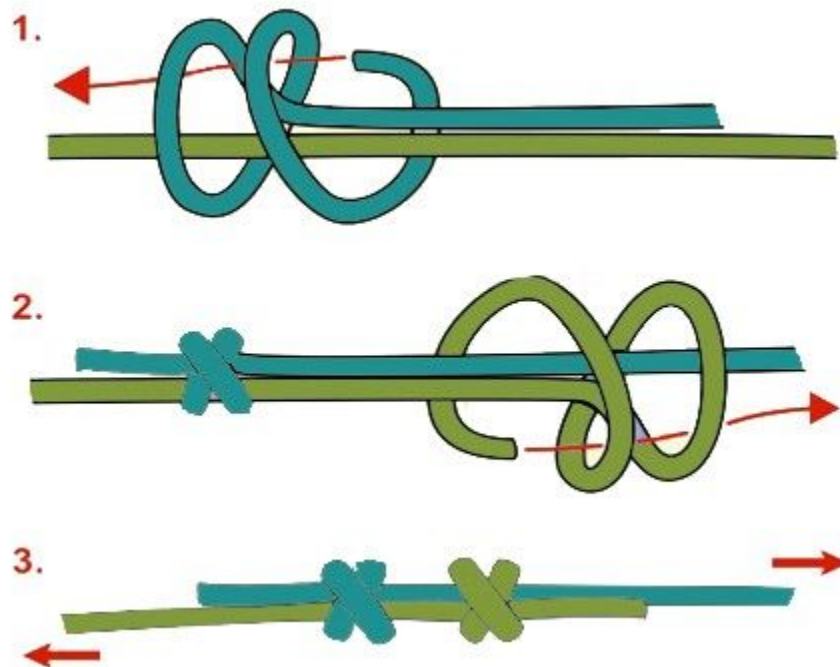
Fig. 99: Double fisherman's knot tying instructions [74]

11.1.3 Electronics Assembly

The current two-sided protoboard approach is useful for conserving space, but is difficult for assembly. Connections for battery power and sensor attachments should be set up so that they are just an attachment away from an appropriate pin on the Arduino Nano. Once all attachments are ready to be connected to the nano, the Nano is placed on the underside of the board, such that the pins stick up to the top (the side where the resistors and battery connections have been made).

11.1.4 Biointerface Assembly

Once the sensor pockets are sewn and positioned on the compressive undergarment with fabric, the wires need to be looped through additional support loops on the shirt. There are two critical points to making sure the biointerface operates properly: ensuring that the sensor does not fall out of the sensor pocket and ensuring that the sensor pocket stays completely attached at its two endpoints.

11.2 Design for Manufacture

As discussed, the emphasis of this project was on the mechanical design and biointerface of an electrically powered prosthetic hand. Design for manufacturing was not meant to be the emphasis for this undergraduate team in the first year. That being said, HELP Hand is projected to be a long-term ongoing project, and so designing for manufacturing in the Indian context is among the most critical next steps.

Within the current mechanical system, there are a number of key factors to consider in developing a manufacturing process. The use of tendons is among the most significant current assembly challenges. As seen in the video linked in Chapter 11.1, there is a meticulous knot tying process that is used to connect the tendons to the fingers, pulley and motor. For practical implementation of this hand, this process would have to be standardized and/or automated. Additionally, the palm structure is extremely geometrically intricate, and as a result, it might be very challenging to produce in metal

(as originally intended). This means 3-D printing might be a viable solution for the final product, but therefore research into the accessibility of 3-D printing in India must be conducted.

The electronics, currently being implemented with a large microprocessor, could certainly be simplified. Development of a PCB could leave enough room to store the battery within the electronics cavity of the palm. This possibility may also make it wise to consider a more easily detachable palm cover without sacrificing waterproofing. Additionally, it is important that all distributors of electronic components do business regularly and consistently with the areas in India where BMVSS operates.

The current biointerface still requires standardization and specification of the design in order to move into a manufacturing process.

Chapter 12: Engineering Standards

12.1 Manufacturability

Manufacturing the HELP Hand included both short term and long term considerations. The manufacturing process for different prototypes and different subassemblies will vary drastically. In the short term, prototypes and the first overall iterations of the HELP Hand will be manufactured using Santa Clara University's resources. In the long term, however, we hope to develop a manufacturing process such that the HELP hand can be manufactured solely in India.

12.1.1 Short Term

For the current scope of the project, within the confines of the School of Engineering Senior Design Project, all manufacturing was conducted in the RSL, the Maker Lab, or the Mechanical Engineering Machine Shop. All of these facilities are owned and operated by Santa Clara University, and each workspace has its own associated protocol and working set of guidelines. In using these workspaces, all of these associated guidelines were followed closely, and all team members were required to notify the rest of the team should concerns arise.

Each component of the HELP Hand were designed for manufacturability with these resources in mind. Each workspace had limited time and throughput, and the team had to plan ahead for this. By keeping the above considerations in mind, we ensured that the manufacturing process went smoothly and efficiently and ensured that a final deliverable was possibly by the end of the 2018-2019 academic year.

12.1.2 Long Term

Manufacturing in India, while not an immediate concern, remains as an important consideration throughout the 2018-2019 senior design year. The 2018-2019 design team kept mass manufacturing techniques in mind in order to ensure that future design

for manufacturing was possible given our design. Future teams should conduct research on the state of manufacturing in India such that a fully documented manufacturing process can be developed and provided to BMVSS.

12.2 Health & Safety

Both the senior design team and the end user were considered when it came to the health and safety concerns of the HELP Hand project / product. Safety was placed above all other factors throughout senior design, and help was be sought for any complex or concerning cases we encountered.

12.2.1 Senior Design Team

The health and safety concerns for the design team were almost entirely related to manufacturing, assembly, and testing. This manufacturing included sub assembly builds, prototype builds, and also the final project build. As for any case of manufacturing, we ensured that our manufacturing process was safe. Safety concerns related to our project included, but were not limited to, proper machine use / material use and adherence to relevant guidelines. Assembly and testing included the aspects of the project where parts came together and thus additional care was taken to ensure that the parts functioned properly when interfaced. All university guidelines were followed for each respective workspace being used to ensure that safety was paramount.

12.2.2 End User

The health and safety concerns for the end user are almost entirely related to operation. Using the HELP Hand must not put the user at risk in any way and must not pose any long term health concerns. This was be addressed during the testing phase of the senior design project, and all necessary material research was conducted to ensure that the user was safe.

12.3 Social

The HELP Hand, by empowering the user, will also have a social impact on the individual. A primary concern and design constraint of this project was anthropomorphism. As emphasized throughout this report, amputations are highly stigmatized in India. By creating an anthropomorphic hand, we have potentially reduced the social stigma from the person and allowed them to more easily assimilate into society.

Designing to this need greatly affected many of the design decisions that needed to be made, primarily in regards to the actuation mechanism and the outer glove of the hand. Both the static and dynamic aspects of the hand needed to be as human like as possible in order to avoid the social stigma so readily placed on these individuals. By factoring in the customer need of anthropomorphism, we have increased the social standing of the individual in India and have contributed to their empowerment.

12.4 Economic

It is our hope that the HELP Hand will have an impact on the local economies where it is launched, that is, where individuals are using and experiencing this device. The goal of this project, as stated in the introduction, is to re-empower amputees to pursue the life that they desire. Because this prosthetic is aimed at the white collar, urban labor force, by re-empowering amputees we are simultaneously bolstering the labor force.

With the Help Hand, individuals who could not obtain a job will now have a greater chance at doing so, and those who were employed will now have a greater chance of increasing their own working efficiency. In both cases, the individual is more marketable to society and will be better able to contribute their own potential. Additionally, if manufacturing in India is kept in mind, there would be a need for a manufacturing labor force to support the demand of this product. If a manufacturing plan were to be fully implemented in India, the economy would benefit from both the supplier and consumer sides.

12.5 Ethical

As people, and in particular as engineers, it is important that we are conscientious of our ethical duties. Technological devices have immense impact upon individuals, societies, and nature, so the engineering design process ought to be permeated by ethical questioning and discussion. In the case of our project, the HELP Hand, the impact of the device on the international society as well as the individual rights of the people involved have been driving forces throughout our design project, from project selection to technical decisions.

12.5.1 Ethical Analysis of the Concept

Before investing our efforts, the support of Santa Clara University, and the support of BMVSS, we carefully considered the ethical impact of the HELP Hand. We considered the project from both the social contract and deontological perspectives as we wanted to attend to both the wellbeing of our larger society and the rights of the individuals involved.

Social contract theory emphasizes the ethicality of actions that promote the stable functioning of society. Critical to this stability is justice; unrest develops through the feeling that equal members of society are treated unequally and as such that the society in question is not beneficial to the mistreated individual. Mutual and just benefit is what encourages individuals to participate in organized society, and without universal benefit, the society is likely to experience disturbances. In order to evaluate the justness of a society, philosopher John Rawls proposed envisaging oneself behind a veil of ignorance such that one knows of none of their particular traits or characteristics. One is sure only that they possess universal human properties, and they know nothing of their societal position, standing, intelligence, education, race, physical state, etc. The just and therefore ethical thing is that which one would accept from behind the veil of ignorance.

From behind the veil of ignorance, it is most important to improve the standing of those in society who are the worst off. It is from this principle that the importance of the HELP Hand becomes apparent.

While the social contract has traditionally been applied to explicitly organized and unified societies sharing a single governing body, we believe that in today's world it is apropos to consider some international regions as constituting a society as they are involved in mutually beneficial cooperation. Besides the growing presence of international governing bodies and agreements, the exponential increase in international socioeconomic activities has produced an international society which is defined by reciprocal interest and interaction rather than national borders. The relationship between India and the United States is a prime example of such an international society, as evidenced by trade of services and goods between India and the U.S. totaling $126.2 billion in 2017 [75]. The informal society formed between India and the U.S. is founded upon a mutual benefit to both parties, and just as is found in national societies, perceptions of injustice in the relationship would encourage unrest and potentially the disintegration of this mutually beneficial relationship.

As an Indian-American society, the relationship between American consumers and Indian manufacturing is currently imbalanced. The U.S. imports many goods from India (as evidenced by a $27.3 billion trade deficit) in part because they produce the goods for cheaper than the U.S. can domestically [75]. However, this price decrease is derived from lower worker wages and more dangerous working conditions [76]. Approximately 23,500 amputees are added to the amputee population in India annually, and among these trauma related amputations are much more prevalent than in the U.S. [77] The United States is therefore directly encouraging conditions which lead to elevated numbers of amputations in India by purchasing Indian goods.

Finally, it is just to elevate the position of the amputee population in India. Being able to perform basic daily activities is critical for enabling Indian individuals to make a living, and therefore the Indian amputee population suffers economically as the result of their

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amputation [3]. The majority of Indians experience economic stress regardless of physical limitations, living on less than a dollar a day of income, and most amputees are unemployed or work in poor agricultural settings after their amputation [78]. Producing an economically and geographically accessible prosthetic device which is specifically designed for the amputee population in India will hopefully assist in mitigating the negative impacts of amputation on Indian amputees and therefore promote an increased quality of living. Acting to elevate the position of Indian amputees through the development of the HELP Hand is ethical in its benefit to a population near the bottom of the Indian-American society.

Such a prosthetic hand will also help to restore the individual rights of Indian amputees. Deontological ethics argues that all human beings have individual value and dignity as rational beings. As beings with inherent value, all people have indispensable rights that are fundamental to their human dignity and which ought to be respected in all cases. Attending to these rights ensures that all people be treated as an ends in themselves rather than as merely a means to an end.

The design of the HELP Hand contributes to an effort to restore rights such as that to bodily integrity, to equal opportunity, and to the ability to make choices about the life one will lead. Through the loss of a limb due to unsafe working conditions and/or lack of medical care, these rights have been violated. The individual has been used as a means to profit without concern for their individual human dignity. The HELP Hand will never be able to return the hand to the amputee, but by providing technology capable of assisting the individual, we hope that we will contribute to decreasing the continuing effect of the amputation. The goal of the HELP Hand is therefore to increase the human dignity of the individual as well as to promote just function of society.

Before addressing the ethics of our design approach, we would like to address why it is ethical for us to accept a role in this project. Many resources have been directed towards our design efforts, and as such we ought to consider our capability to help as well as our limitations.

As an excellent engineering university, Santa Clara University has value to add to the project. Universities in general are great breeding grounds for new ideas and for coordinated research project. SCU in particular has the infrastructure and resources required to support a committed and continued effort to provide BMVSS with a successful prosthetic hand. Knowledgeable and experienced faculty from the mechanical engineering, bioengineering, and public health fields have provided ongoing support to various student groups. Furthermore, ample lab spaces and funding have been provided so as to give the project its optimal chance at success.

However, we recognize our limitations as professors and students at SCU and as such have ongoing contact and feedback from Indian prosthetists Dr. Pooja Mukul as well as Silicon Valley engineers involved with BMVSS. Finally, we are attending a global health conference to receive feedback about our design approach from specialists, and we continue to apply to similar opportunities.

12.5.2 Ethical Analysis of the Design

Given the established ethical obligation to pursue this project, the specific ethical concerns contained within the project must be broken down further. Various individuals and entities have stake in the outcomes of this project including the product user/amputee, BMVSS, Santa Clara University, and the broader environment.

We are considering the ethical implications to the product user in the context of John Rawls's theory on justice. Social contract theory and the Rawls veil of ignorance forces us to remove biases and look at the needs of individuals in the minimum position. Similarly, human-centered design focuses on stripping our own conceptions and using individual human perspective and contexts to solve real-world problems. Both ideas focus on using empathy to understand the needs of other individuals. As a result we elected to take a human-centered design approach towards our engineering decisions, focusing on customer needs and contexts before diving into technical engineering problems. Successfully implementing a human-centered design approach is dependent

on gaining first-hand customer empathy. Utilizing our partnership with BMVSS, Dr. Pooja Mukul, who works first-hand with amputee patients, was able to provide context into the challenges and needs that our customers face.

Creating an anthropomorphic (human-like) hand is one of the most critical customer needs in our design context. Prosthetics users in India face a starkly different social context than those in the western world. In the United States, an amputee with a complex, expensive, "bionic" arm could expect other members of western society to be fascinated and impressed by the technology. In contrast, Indian culture stigmatizes amputations and amputees. "Hook hand" prosthesis that are robust and powerful are uniformly rejected in India due to their lack of anthropomorphism. Amputees would prefer to wear a passive (non-functional) prosthetic that simply looks like a hand, than to use a "Hook hand" that may draw attention. As a result, designing for anthropomorphism was a clear need of our customer. With this knowledge, two important design decisions were made. The first fundamental requirement derived was that the hand must be able to fit into a prosthetic glove. Commercially available prosthetic gloves look remarkably real, and allow any mechanical structure to be concealed in favor of anthropomorphism. In addition, a compliant grasp was deemed a requirement such that the actual movement of the prosthetic more closely represented the complex human hand.

Next, for any prosthetic user, comfort is necessary to making use of the hand a pleasant experience. Target specifications for size, weight and weight distribution of the hand were all selected to guide the overall engineering design. These factors impact material selection in the engineering process, but ultimately have an affect on the well-being of the user. An uncomfortable prosthesis is a nuisance to the user. If comfort is entirely deficient, the prosthetic may not be used wasting the time and effort of all stakeholders. In addition to the physical properties of the prosthetic, comfort must be considered in the design of the biointerface. In order to maximize comfort in the biointerface, we decided to make the hand electrically powered. A person using their functional human hand does not have to exert physical energy to close their hand. Similarly, we elected to

have a biointerface that required as little physical energy as possible to trigger a battery powered motor which will perform the mechanical work.

Given the complex nature of each individual person, modularity and customizability are important customer needs as well. Aesthetic and physical design considerations in this project are dependent on race, gender and size. In order to best fulfill a duty to restore livelihood to all amputees, our design must work well for all different populations. This requirement also contributes to the decision to fit the prosthetic into a glove, as gloves can easily be made into different sizes and skin tones.

In addition to using a human-centered design approach to ensure ethical engineering decisions, the maxim of "first do no harm" was simultaneously weighed into all decisions. The American Society of Mechanical Engineers (ASME) code of ethics states that the "safety, health and welfare" of the public be of the utmost importance to all engineers [79]. Hence, ensuring the physical safety of our device was a constant design priority. This led to the decision to use a low-voltage battery with relatively low maximal current output. Additionally, the maxim of "first do no harm" can be extrapolated to inform the performance specifications of our product. It is essential that the hand we design be an overall more pleasant experience for the user than the currently commercially available hands. Otherwise, the hand will be both a waste of resources and a major inconvenience to the amputee.

Beyond the user, an ethical obligation is held to BMVSS. Trust between entities is essential in the maintenance of societal function and therefore we hold a duty to create and maintain trust. BMVSS has provided the scope of this project, the means to accomplish it, and funding to support the research investment. In accepting their investment, we accept a duty to meet, and hopefully exceed, the expectations they have. This has made understanding the expectations of BMVSS paramount in the design process. Regular phone calls with Dr. Pooja Mukul in India have occurred to deepen our understanding of customer needs and gain feedback relating to ongoing designs. Maintaining this communication allows a positive relationship between our

design team and BMVSS which can help maximize the application of our project's efforts.

Like BMVSS, Santa Clara University has invested great resources from professors, research labs and research funds to ensure the success of this project. The project has been particularly well-supported due to its humanitarian nature. Again, this investment implies a duty to return from our team. Additionally, as this project promotes humanitarian engineering for the overall school, it can be seen as a fuel or inspiration for additional efforts centered around social justice.

Finally, while it is the less-obvious stakeholder in the HELP Hand, the environment holds great ethical consideration. Research and development of the hand requires the acquisition and use of vast materials, many of which will eventually be of no use to the project. Furthermore, once the hand is brought to a mass-production environment, it will require sourcing of various materials. Taking resources from the environment is the only way to develop a project like this. It must be considered that extraction from the environment bears negative long-term consequences upon all humans if not handled properly. In the scope of senior design, we aim to minimize our environmental footprint by passing on unused project materials for re-use. Moving into a production environment, it is essential that the HELP Hand be produced from sustainable materials. We have elected to use aluminum for the hand structure, a widely-available and recyclable metal. Additionally, the hand has been designed for ease-of-maintenance, featuring a removable cover that allows prosthetists to repair mechanisms if there is damage to the hand. This is intended to add product life and minimize waste. Moreover, we chose to use sensors, with long-term part lives as the biointerface. Flex sensors were selected over traditional wet electrodes, which are disposable and create a great deal of waste. Finally, one of the key product specifications for part selection has been cycles to failure. We hope to design the hand to be rated for over one million cycles to failure, making it long-lasting and reliable.

12.5.3 Summary

Social contract theory and deontology inform us of the ethical justification and obligation to pursue the HELP Hand project. Using this ethical backing, we selected a human-centered design approach to determine the needs of our customer and guide our engineering decisions. These guidelines and their motivations will be passed on to subsequent design teams.

Additionally, there are ethical concerns in the use of human testing with the prosthesis. In order to conduct human testing outside of the walls of the University, the design team started the online application process for Santa Clara University Institutional Review Board approval. By starting the IRB approval process through the Office of Research Compliance and Integrity, future design groups will be prepared to ethically collect user feedback.

Chapter 13: Summary and Conclusions

13.1 Senior Design Evaluation

Our electrically powered prosthetic hand aimed to satisfy the needs of unilateral, transradial amputees with white-collar lifestyles in India and provide direct humanitarian value through the infrastructure of BMVSS. Overall, the work done in the first year of this project has made great strides in achieving this goal.

The initial prototype that has been completed for senior design has met and exceeded expectations to our advisors and customers. Representatives of BMVSS have expressed satisfaction and excitement with the progress made thus far. They have particularly been excited by the innovative nature of the tendon-actuated pulley differential mechanical design which is not a common approach taken in prosthetics research.

13.2 Suggestions for Improvement

While the final prosthetic hand design met all of the overall system requirements, the team would have liked to test a number of different design options should time have permitted.

Before designing any further, user feedback should be gathered to determine how the prosthetic device performs during the daily life of a user. This could be achieved by both customer surveys and direct user testing. Examples of questions to be asked in a customer survey are included in Appendix F. This feedback could then be analyzed and used to more specifically meet the needs of the customer and ensure that the first 'launch' of this product has the highest chance for success. Measures should be taken to ensure that testing is well documented and occurs under whatever government / health oversight is needed.

After conducting user testing, we suggest that the next design teams focus on a number of things:

For the biointerface, EMG control should be further explored. We determined that it would be an unreliable actuation input method because of our inability to properly debug the system as a result of time constraints. In the future a dedicated team could further refine this type of system and implement it.

For the electronics, a pcb board could be implemented to further shrink down the electronics and potentially allow for the battery to be mounted within the palm. Other motor / actuator options should be explored that would allow for a stronger grip but while still be incorporated into the current profile of the system.

Lastly, for the actuation mechanism, future teams should revisit the implementation of 2-joint fingers in order to achieve a more compliant and anthropomorphic grip. Different tendon routing options should also be explored along with tendon material selection.

13.3 Further Guidance

Knowing that this is a multi-year and multi-team project, it was extremely important for this senior design team to package all of the deliverables and materials in a way that could be easily handed off. The long term success of this project and the partnership with BMVSS is highly dependent upon the cooperation between old and new teams and thorough communication.

We have compiled the following items onto a shareable drive and also a hard disk to be handed off to the next design team:
- Senior design thesis and presentation
- SolidWorks CAD / FEA / detail drawing files
- Video / picture documentation
- Arduino microcontroller codes
- All raw materials, hardware, and assemblies

- Research archive

This contact information for this senior design team will be provided upon request to facilitate a smooth transition.

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Appendix A: Detail Design Drawings

Actuation Subsystem Detail Drawings
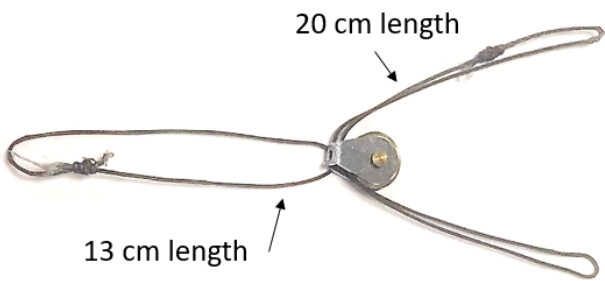
Fig. A-1: Assembled pulley actuation subsystem

Fig. A-2: Detail drawing of modified pulley

Fingers

Fig. A-3: Detail drawing of index finger

SANTA CLARA UNIVERSITY
HELP Hand

TITLE:
Index Finger

SIZE: A   PART. NO. F001   REV A

SCALE: 1:1   WEIGHT: TBD   SHEET 1 OF 1

MATERIAL:
2024-T4
Aluminum Alloy

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
FRACTIONAL ± 1/2
ANGULAR: MACH ± 1° BEND ±1°
ONE PLACE DECIMAL ±0.5
TWO PLACE DECIMAL ±0.05

	NAME	DATE
DRAWN	Jamie Ferris	5/25/19
CHECKED		
DESIGNED	Jamie Ferris	4/26/19

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159.2°
R9.24
12.00
16.00
R11.08
Ø2.00
26.00
16.00
R7.00
Ø6.05
6.35

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Fig. A-4: Detail drawing of middle / ring finger

SANTA CLARA UNIVERSITY
HELP Hand

TITLE:
Middle/Ring Finger

SIZE **A** | PART. NO. F002 | REV **A**

SCALE: 1:1 | WEIGHT: TBD | SHEET 1 OF 1

MATERIAL:
2024-T4
Aluminum Alloy

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
FRACTIONAL ± 1/2
ANGULAR: MACH± 1°   BEND ±1°
ONE PLACE DECIMAL   ±0.5
TWO PLACE DECIMAL   ±0.05

	NAME	DATE
DRAWN	Jamie Ferris	5/25/19
CHECKED		
DESIGNED	Jamie Ferris	4/26/19

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155°
159.2°
12.00
R9.24
16.00
R11.08
26.00
16.00
2.50
R7.00
R2.98
6.35

164

Fig. A-5: Detail drawing of pinky finger

Finger insert from prosthetic glove used to cover prosthesis.

Cut here to isolate pinky

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
FRACTIONAL ± 1/2
ANGULAR: MACH± 1° BEND ±1°
ONE PLACE DECIMAL   ±0.5
TWO PLACE DECIMAL   ±0.05

	NAME	DATE
DRAWN	Jamie Ferris	5/28/19
CHECKED		
DESIGNED	Jamie Ferris	4/27/19

MATERIAL:

PROPRIETARY AND CONFIDENTIAL

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Prosthetic Glove Finger Insert

DO NOT SCALE DRAWING

SANTA CLARA UNIVERSITY
HELP Hand

TITLE:

Pinky

SIZE **A**   PART. NO. **F003**   REV **A**

SCALE: 5:1   WEIGHT: TBD   SHEET 1 OF 1

Fig. A-6: Detail drawing of thumb

Produced from 3D scan
of prosthetic glove used
to cover prosthesis

SANTA CLARA UNIVERSITY
HELP Hand

TITLE:
Thumb

	NAME	DATE
DRAWN	Jamie Ferris	5/28/19
CHECKED		
DESIGNED	Jamie Ferris	4/25/19

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
FRACTIONAL± 1/2
ANGULAR: MACH± 1° BEND ±1°
ONE PLACE DECIMAL ±0.5
TWO PLACE DECIMAL ±0.05

MATERIAL:
PLA

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SIZE	PART. NO.	REV
A	F004	A

SCALE: 5:1   WEIGHT: TBD   SHEET 1 OF 1

Palm St

Fig. A-7. Detail drawing of palm structure (1)

Fig. A-8: Detail drawing of palm structure (2)

Fig. A-9: Detail drawing of palm cover 1

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
FRACTIONAL ± 1/2
ANGULAR: MACH ±1° BEND ±1°
ONE PLACE DECIMAL ±.5
TWO PLACE DECIMAL ±.05

MATERIAL:
Acrylic

NOTES:

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	Evan Misuraca	5/28/19
CHECKED	Michael Mehta	5/28/19
DESIGNED	Evan Misuraca	5/28/19

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68.00

1.59

18.54
7.00
Ø 1.00 × 4
1.50
11.68
3.00
1.50

15.43
28.15

Fig. A-10: Detail drawing of palm cover 2

Fig. A-11: Detail drawing of palm shaft

Ø 5.90

2.50

50.00

	NAME	DATE
DRAWN	Michael Mehta	5/30/19
CHECKED	Evan Misuraca	5/30/19
DESIGNED	Michael Mehta	5/3/19

SANTA CLARA UNIVERSITY
SENIOR DESIGN TEAM 6 : HELP Hand
TITLE:

Palm Shaft

SIZE **A** PART. NO. **P004** REV **A**

SCALE: 2:1 WEIGHT: 13.11g SHEET 1 OF 1

B

A

2

1

Fig. A-12: Detail drawing of bearing shaft
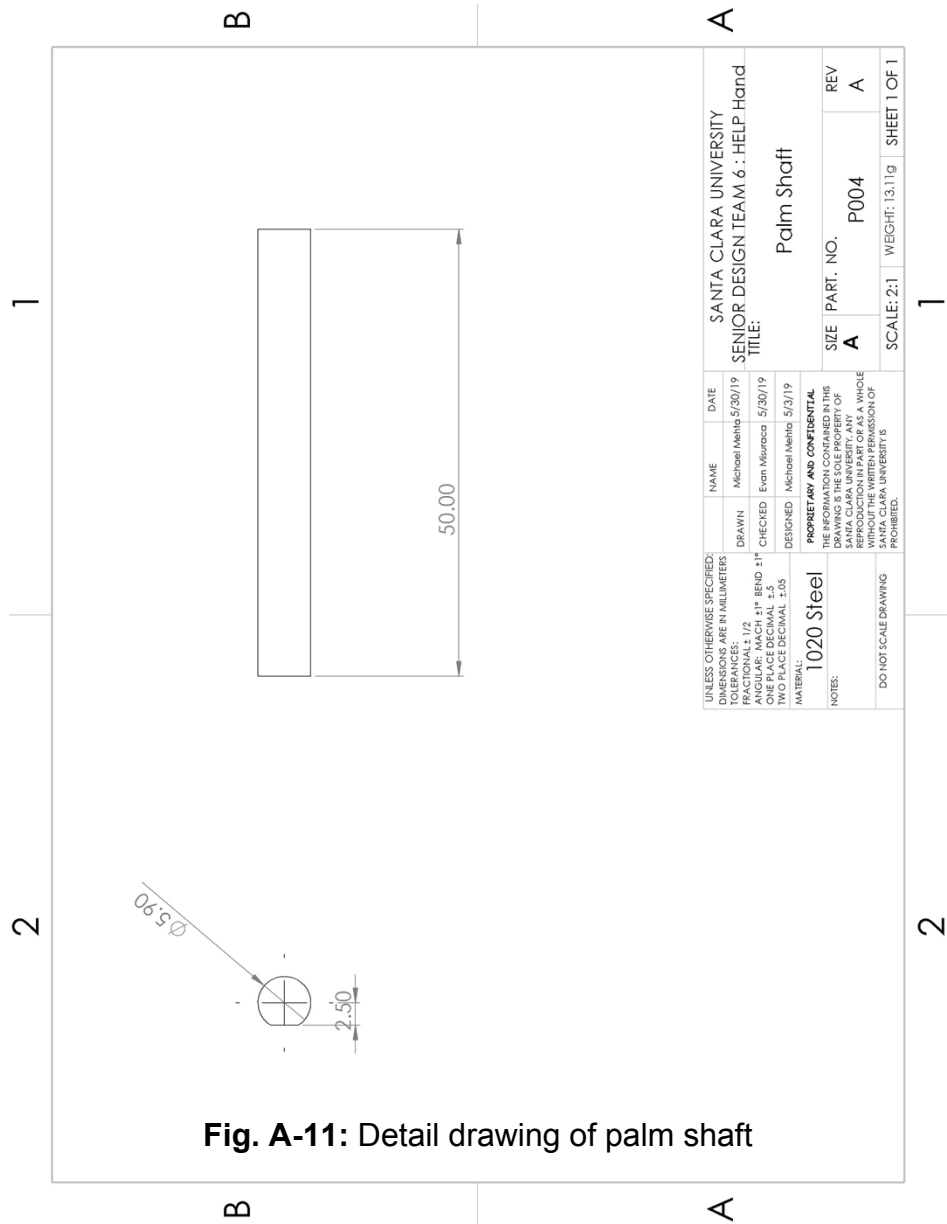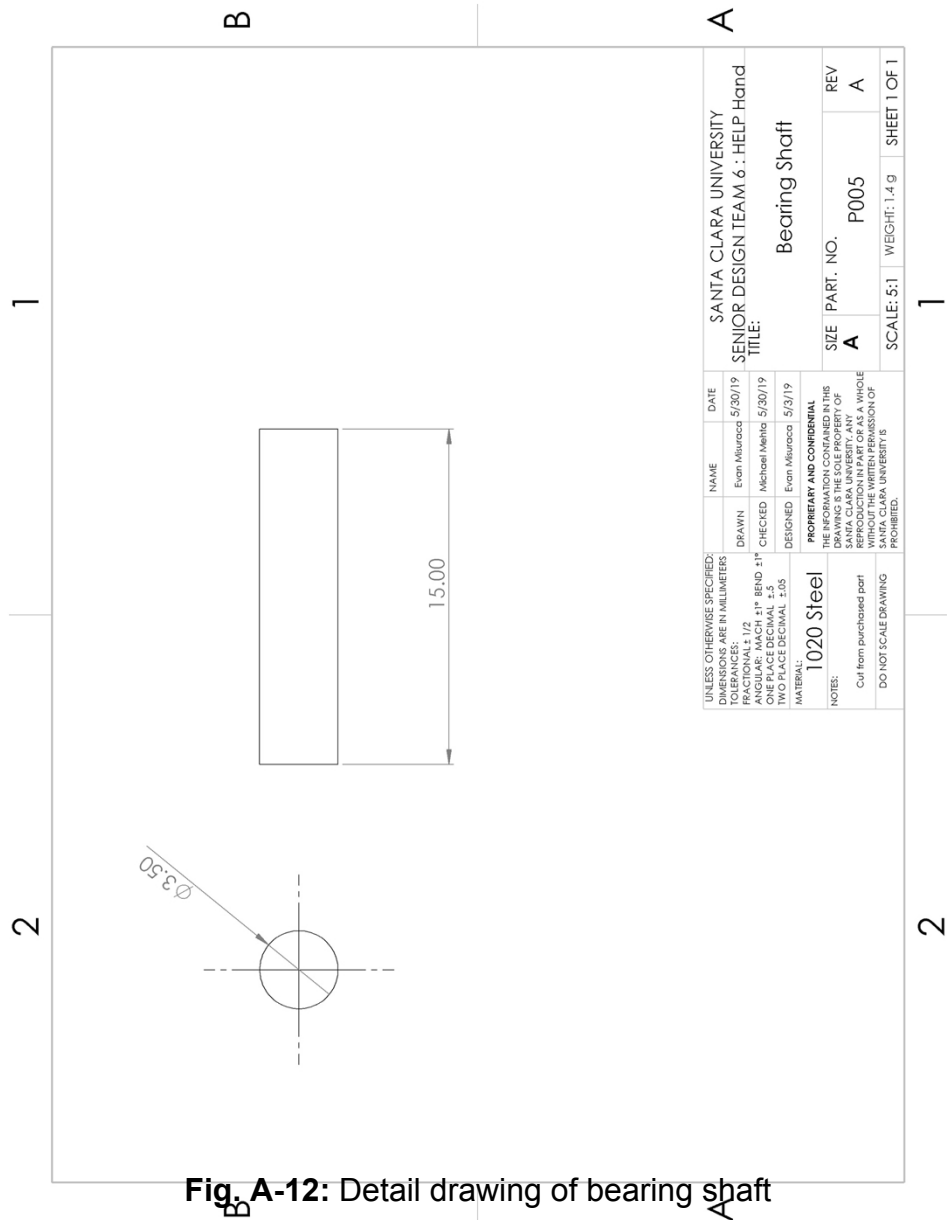
Electronics Subsystem Detail Drawings
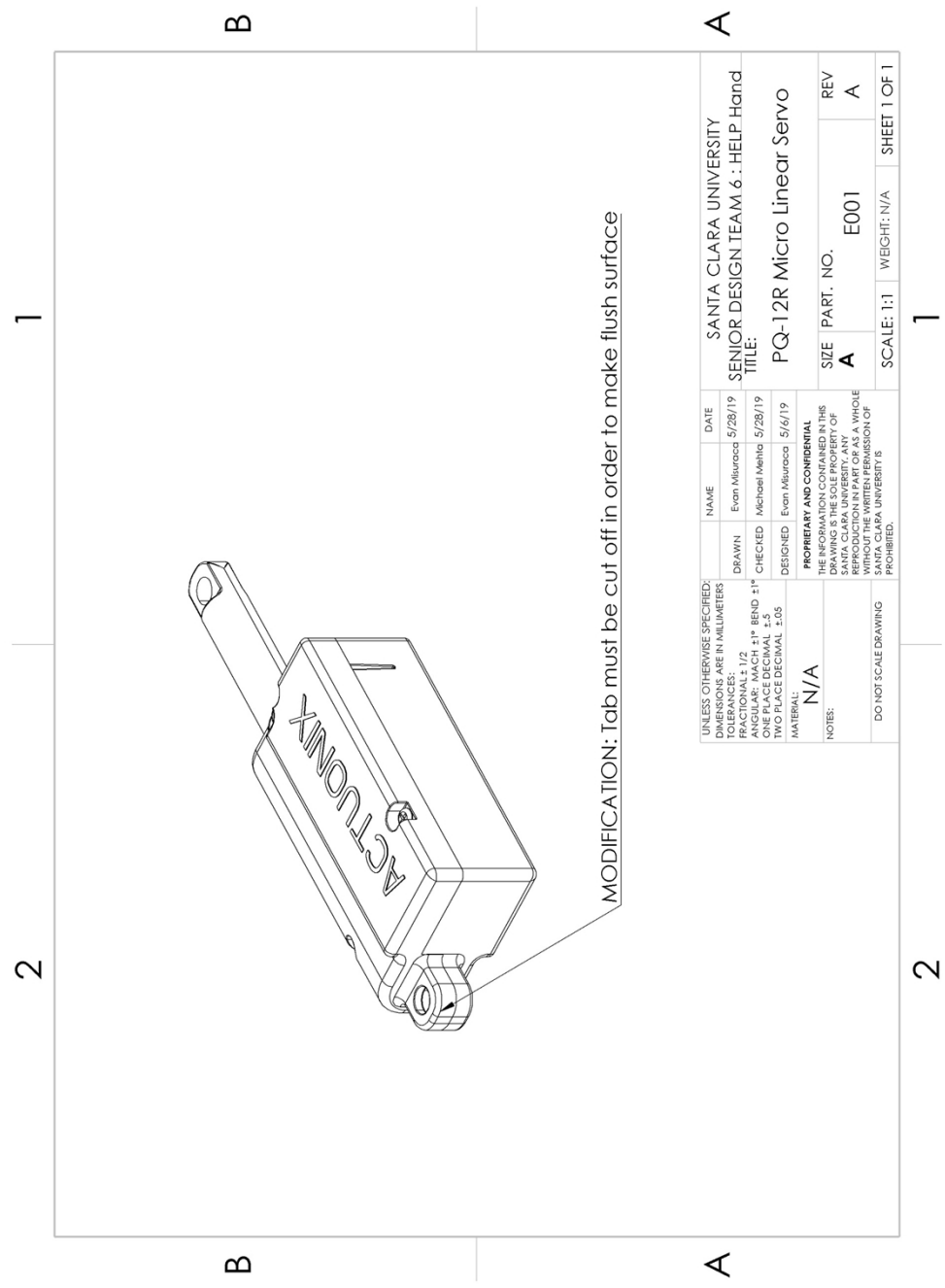
Fig. A-13: Detail drawing of linear actuator modification

Appendix B: Timeline
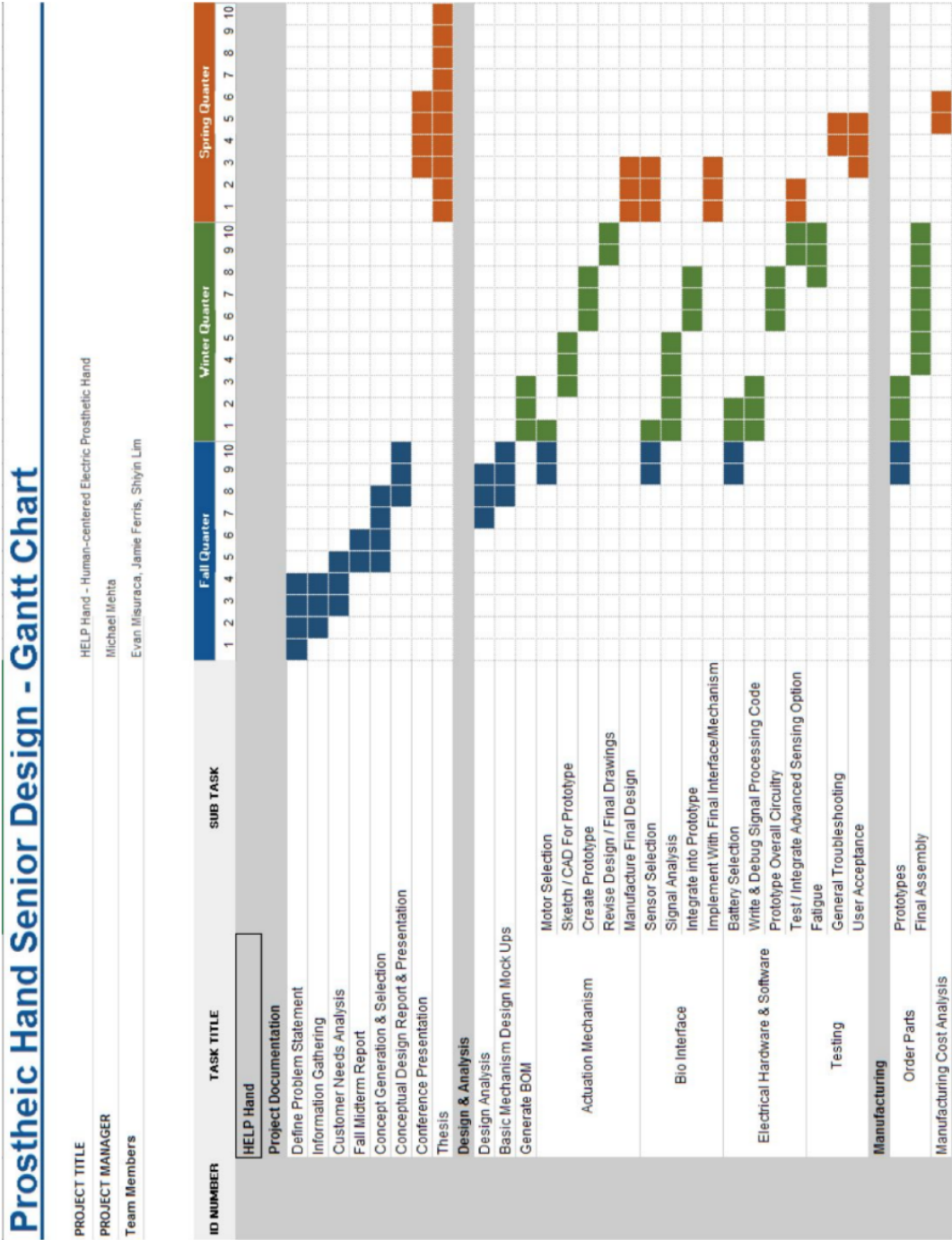
Fig. B-1: Project Timeline Gantt Chart

Appendix C: Budget Spreadsheet

A partial screenshot of the team's budget spreadsheet is provided in Fig. C-1. 128 different items were purchased over the course of the year. The entirety of the budget is detailed upon request and will be provided on the thumb drive passed on to future teams.

Date	Purchaser	Item Name	Vendor	Part Quantity	Package Cost	Category
1/5/2019	Jamie	MyoWare Cable Shield	SparkFun	1	$4.95	Bio-Interface Components
1/5/2019	Jamie	MyoWare Muscle Sensor	SparkFun	1	$37.95	Bio-Interface Components
1/5/2019	Jamie	S&H & Tax	Frys	1	$6.32	Tax/S&H
1/13/2019	Evan	Protoboards	Frys	4	$4.99	Basic Electronic Components
1/13/2019	Evan	Wall Power Supply	Frys	1	$7.99	Power Supply
1/13/2019	Evan	Voltage Regulator Module	Frys	1	$9.99	Power Supply
1/13/2019	Evan	AA Batteries	Frys	8	$1.99	Power Supply
1/13/2019	Evan	Micro-USB For Arduino	Frys	1	$2.99	Processor
1/13/2019	Evan	6V Battery Holder (AAs)	Frys	1	$1.79	Power Supply
1/13/2019	Evan	Tax	Frys	1	$2.75	Tax/S&H
1/13/2019	Mike	H-Bridge (Large)	Banggood	2	$3.06	Basic Electronic Components
1/13/2019	Mike	H-Bridge (Small)	Banggood	1	$2.96	Basic Electronic Components
1/13/2019	Mike	Current sensor	Banggood	2	$5.56	Sensors
1/13/2019	Mike	Tax & Insurance	Banggood	1	$2.01	Tax/S&H
1/13/2019	Mike	Motor Input Board B	ServoCity	1	$0.89	Motor
1/13/2019	Mike	Motor Input Board C	ServoCity	1	$0.79	Motor
1/13/2019	Mike	34 RPM Gear Motor	ServoCity	1	$14.99	Motor
1/13/2019	Mike	Motor Mount	ServoCity	1	$5.99	Motor
1/13/2019	Mike	Motor Shaft Pulley	ServoCity	1	$8.99	Motor
1/13/2019	Mike	98 RPM Gear Motor	ServoCity	1	$14.99	Motor

Fig. C-1: Budget Spreadsheet

Appendix D: Supplementary Subsystem Sketches
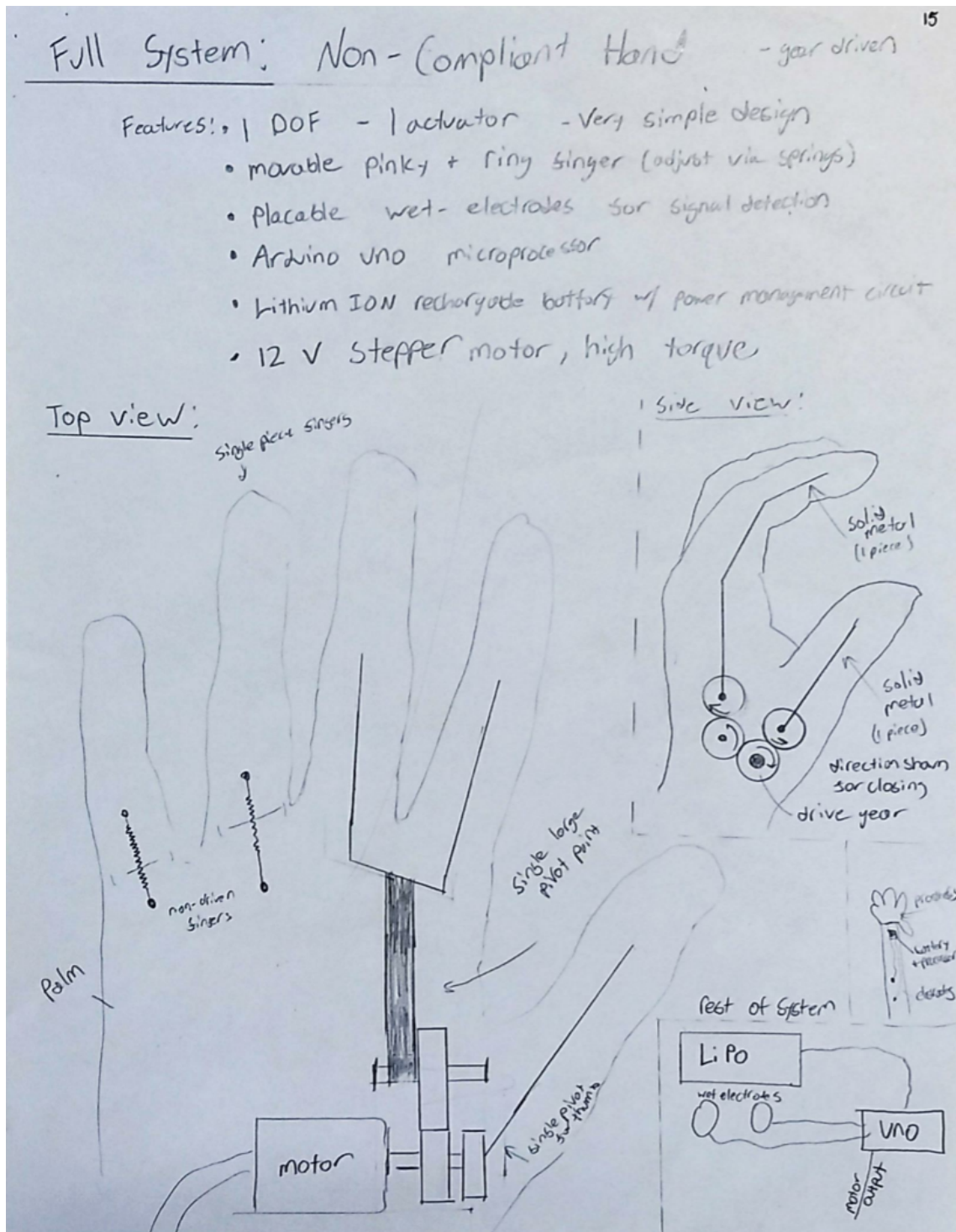
Fig. D-1: Gear-Driven Non-Compliant Hand Sketch

Subsystem: Finger (Joint)

Mechanism: Elastic Belt /Rotational Sliding Joint
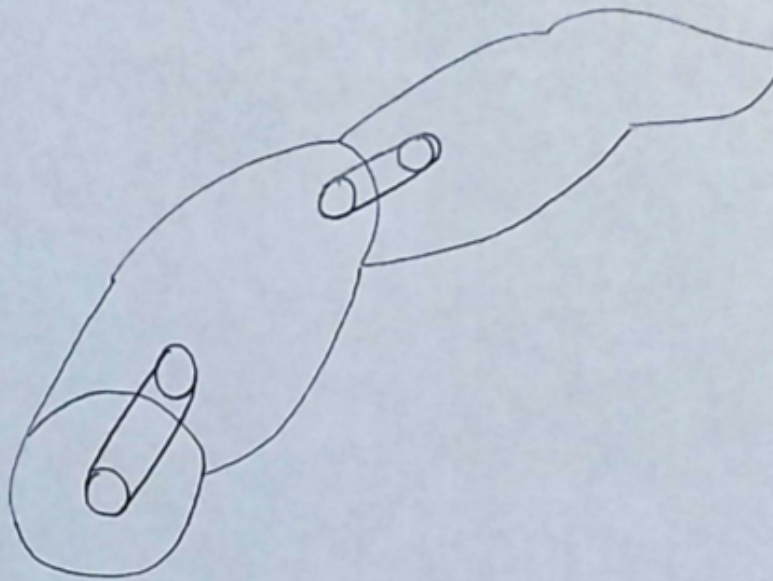
Concept: Rather than using a hinge-like mechanism, this finger slides against other pieces to close, and is held together by an elastic belt (mimicing human anatomy). These joints would be highly resisted to outside sources

Fig. D-2: Elastic Belt / Rotational Sliding Joints Sketch

Subsystem: Palmer Differential

Mechanism: linkage/lever

① = connections to fingers

lets resistance met

more resistance met

will connect to single-piece fingers (essentially single joint attach points)

Side view

Servo motor

to System

retention springs
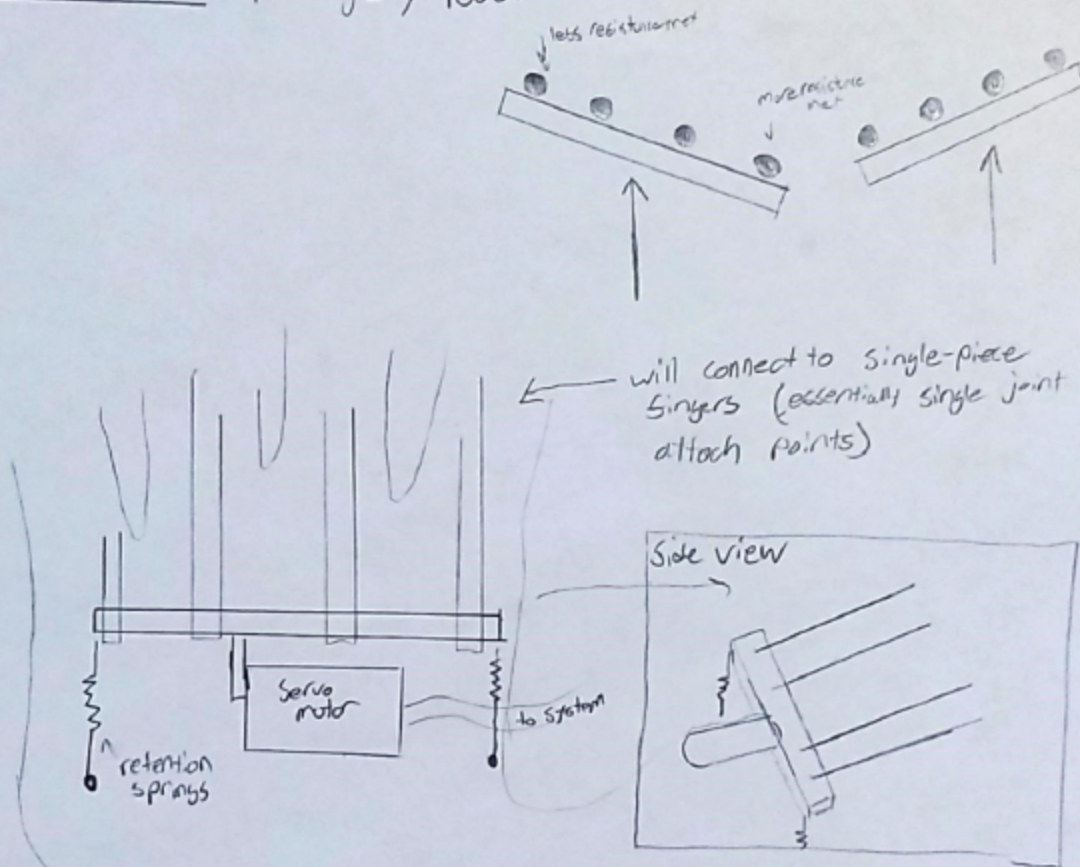
Concept: A main servo drives an activation lever that is attached on either end via springs. The springs allow the lever to move in a see-saw motion as can be seen in the upper right figure. When resistance is met by one of the fingers, the lever has the ability to shift and to apply more force to the linkages that have not yet met resistance.

Fig. D-3: Linkage / Lever Sketch

Subsystem: Finger

Mechanism: Linkage

Concept: This concept is for a linkage based figure,
where one part of the linkage is rotated in
order to close the finger. Labels 1, 2
and 3 can be envisioned as the
three bones of the finger, 4, 5 and 6
collectively play the role of tendons.

Source: See [55] from midterm report

Fig. D-4: Linkage-Driven Finger Sketch

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Subsystem: Finger

Mechanism: Slip block differential

mobile joint   fixed joint

driven by Slip block

finger

slip block

object

driving by motor
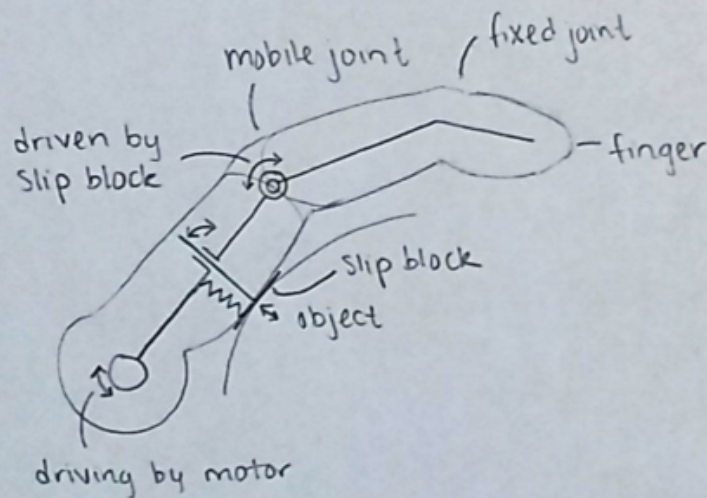
Concept: slip block comes into contact with grasped object which gets results in the transfer of driven rotation from rotation of the proximal phalanx to rotation of the middle phalanx, creating under actuated motion. A spring returns the slip block and therefore the middle phalanx when not in contact with an object.

Source: Zhang, Wenzeng, Chen, Qiang, Sun, Zhenguo, and Zhao, Dongbin. "Passive Adaptive Grasp Multi-Fingered Humanoid Robot Hand with Under-Actuated Function." IEEE International Conference on Robotics & Automation. 0-7803-8232-3: pp. 2216-2221. New Orleans, LA, April, 2004. DOI 10.1109/ROBOT.2004.1.

Fig. D-5: Slip Block Differential Sketch

Subsystem: Finger

Mechanism: Single-joint attach point
- Can be driven in various ways
- Simple solid finger design
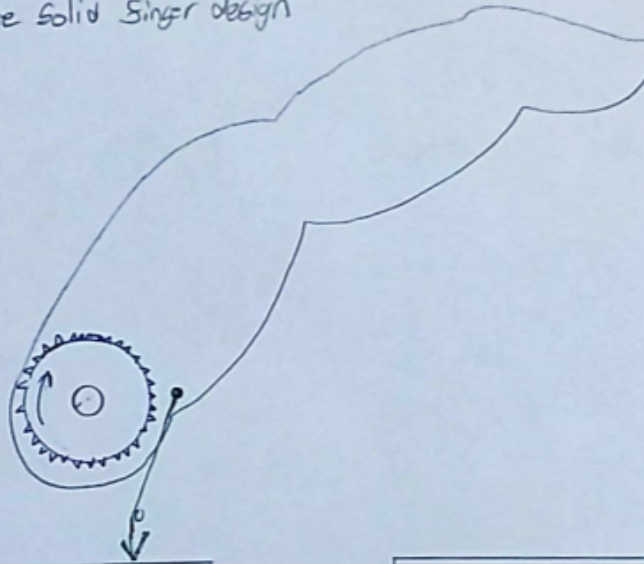
Drive method 1: Tendon
- With this method, a "tendon" will pull at the base of the single piece finger, as indicated above, forcing the finger to rotate around the pivot

Drive method 2: Gearing
- With this method, a gear train will directly drive the base of the single piece finger, as indicated above, forcing the finger to rotate around the pivot

Concept: The solid single joint finger is the most simplistic option for both compliant + non-compliant hands. Whether compliant or non-compliant, the entirety of the finger's motion is driven by the actuation at the base. This eliminates possible unnecessary movement in the flanges, and eliminates additional DOF's. With this design, however, compliance is lost within the finger and so grip force may become a more important consideration.

Fig. D-6: Single Joint Finger Attachment Sketch

Appendix E: Concept Selection Matrices

Team - Decision Matrix Results

	Compliant vs. Non Compliant			Compliant Actuation						Non-compliant Actuation		
	Compliant	Non - Compliant		Tendon w/ pulley	Tendon w/ whiffle	Linkage Lever	Slip block			Linkage	Gear	Tendon
Mike	3.18	3.38		3.90	3.27	2.55	2.08			3.16	1.98	3.90
Evan	3.22	3.15		3.06	2.59	2.62	1.89			3.20	2.53	3.07
Jamie	2.88	3.67		4.08	3.39	3.26	2.25			2.58	2.42	3.53
Average	3.09	3.40		3.68	3.08	2.81	2.07			2.98	2.31	3.50

				RANK			
Total		Tendon w/ pulley	3.44	2	Weight for Compliance Q	0.40	
	Compliant	Tendon w/ whiffle	3.09	4	Weight for Actuation Q	0.60	
		Linkage Lever	2.92	5			
		Slip block	2.48	7			
		Linkage	3.15	3			
	Non-Compliant	Gear	2.75	6			
		Tendon	3.46	1			

Fig. E-1: Decision Matrix Results

Mike - Compliant Vs Non-Compliant Concept Scoring

Selectrion Criteria		Weight	Compliant		Non-Compliant	
			Rating	Weighted Score	Rating	Weighted Score
Manufacturability		10%	2.7		3.3	
	Local	0.7	3	0.27	3	0.33
	India	0.3	2		4	
Feasability		20%	3.9		2.9	
	Simplicity	0.9	4	0.78	3	0.58
	Overall Cost	0.1	3		2	
Robustness		20%	2		4.6	
	Maintinence / Service	0.2	2	0.4	3	0.92
	Durability / Wear	0.8	2		5	
Performance		50%	3.45		3.1	
	Pinch Force	0.1	1		5	
	Size	0.15	5		3	
	Hand weight	0.05	4		3	
	Intuition / Ease of Use	0.2	3	1.725	4	1.55
	Anthropomorphism (static)	0.1	3		2	
	Anthropomorphism (dynamic)	0.1	5		3	
	Bredth of use	0.1	4		3	
	Slip / drop risk	0.2	3		2	
Total Score				3.175		3.38

Fig. E-2: Compliant vs. Non-Compliant Scoring Matrix (Mike)

Evan - Compliant Vs Non-Compliant Concept Scoring			Compliant		Non-Compliant	
Selectrion Criteria		Weight	Rating	Weighted Score	Rating	Weighted Score
Manufacturability		10%	3.7	0.37	2.7	0.27
	Local	0.7	4		3	
	India	0.3	3		2	
Feasability		20%	2.2	0.44	3.9	0.78
	Simplicity	0.9	2		4	
	Overall Cost	0.1	4		3	
Robustness		20%	2.4	0.48	3.6	0.72
	Maintinence / Service	0.2	4		2	
	Durability / Wear	0.8	2		4	
Performance		50%	3.85	1.925	2.75	1.375
	Pinch force	0.1	3		5	
	Size	0.15	4		3	
	Hand weight	0.05	3		2	
	Intuition / Ease of Use	0.2	4		3	
	Anthropomorphism (static)	0.1	3		2	
	Anthropomorphism (dynamic)	0.1	4		2	
	Bredth of use	0.1	5		3	
	Slip / drop risk	0.2	4		2	
Total Score				3.215		3.145

Fig. E-3: Compliant vs. Non-Compliant Scoring Matrix (Evan)

Jamie - Compliant Vs Non-Compliant Concept Scoring			Compliant		Non-Compliant	
Selectrion Criteria		Weight	Rating	Weighted Score	Rating	Weighted Score
Manufacturability		10%	2.7	0.27	4.3	0.43
	Local	0.7	3		4	
	India	0.3	2		5	
Feasability		20%	2	0.4	4.9	0.98
	Simplicity	0.9	2		5	
	Overall Cost	0.1	2		4	
Robustness		20%	2.4	0.48	3.8	0.76
	Maintinence / Service	0.2	4		3	
	Durability / Wear	0.8	2		4	
Performance		50%	3.45	1.725	3	1.5
	Pinch Force	0.1	3		5	
	Size	0.15	3		4	
	Hand weight	0.05	2		4	
	Intuition / Ease of Use	0.2	3		4	
	Anthropomorphism (static)	0.1	4		3	
	Anthropomorphism (dynamic)	0.1	4		2	
	Bredth of use	0.1	4		2	
	Slip / drop risk	0.2	4		1	
Total Score				2.875		3.67

Fig. E-4: Compliant vs. Non-Compliant Scoring Matrix (Jamie)

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Mike - Compliant Actuation Mechanisms Scoring

Selection Criteria		Weight	Tendons w/ Pulleys Rating (1-5)	Weighted Score	Tendons w/ Whiffle Trees Rating (1-5)	Weighted Score	Linkage Lever Rating (1-5)	Weighted Score	Slipblock Rating (1-5)	Weighted Score
Manufacturability		20%	4.1		3.4		3		2	
	Local	0.7	5	0.82	4	0.68	3	0.6	2	0.4
	India	0.3	2		2		3		2	
Feasability		30%	4.8		3.9		2.1		1.2	
	Simplicity	0.9	5	1.44	4	1.17	2	0.63	1	0.36
	Overall Cost	0.1	3		3		3		3	
Robustness		20%	2.2		3.8		3		3	
	Maintinence / Service	0.2	3	0.44	3	0.76	3	0.6	3	0.6
	Durability / Wear	0.8	2		4		3		3	
Performance		30%	4		2.2		2.4		2.4	
	Pinch Force	0.3	2	1.2	2	0.66	4	0.72	4	0.72
	Size	0.6	5		2		2		2	
	Hand weight	0.1	4		4		3		3	
Total Score				3.9		3.27		2.55		2.08

Fig. E-5: Compliant Actuation Mechanism Scoring Matrix (Mike)

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Evan- Compliant Actuation Mechanisms Scoring

Selection Criteria	Weight	Tendons w/ Pulleys Rating (1-5)	Weighted Score	Tendons w/ Whiffle Trees Rating (1-5)	Weighted Score	Linkage Lever Rating (1-5)	Weighted Score	Slipblock Rating (1-5)	Weighted Score
Manufacturability	20%	3.7	0.74	3	0.6	3	0.6	1.7	0.34
Local	0.7	4		3		3		2	
India	0.3	3		3		3		1	
Feasability	30%	3.2	0.96	3.1	0.93	2.1	0.63	1.2	0.36
Simplicity	0.9	3		3		2		1	
Overall Cost	0.1	5		4		3		3	
Robustness	20%	2	0.4	2	0.4	3.8	0.76	2.8	0.56
Maintinence / Service	0.2	2		2		3		2	
Durability / Wear	0.8	2		2		4		3	
Performance	30%	3.2	0.96	2.2	0.66	2.1	0.63	2.1	0.63
Pinch force	0.3	3		2		3		3	
Size	0.6	3		2		2		2	
Hand weight	0.1	5		4		2		4	
Total Score			3.06		2.59		2.62		1.89

Fig. E-6: Compliant Actuation Mechanism Scoring Matrix (Evan)

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Jamie - Compliant Actuation Mechanisms Scoring

Selection Criteria	Weight	Tendons w/ Pulleys Rating (1-5)	Weighted Score	Tendons w/ Whiffle Trees Rating (1-5)	Weighted Score	Linkage Lever Rating (1-5)	Weighted Score	Slip Block Rating (1-5)	Weighted Score
Manufacturability	20%	4.7	0.94	3.7	0.74	5	1	1	0.2
Local	0.7	5		4		5		1	
India	0.3	4		3		5		1	
Feasability	30%	4.9	1.47	4.1	1.23	4.1	1.23	2.1	0.63
Simplicity	0.9	5		4		4		2	
Overall Cost	0.1	4		5		5		3	
Robustness	20%	2.2	0.44	2	0.4	2	0.4	2.6	0.52
Maintinence / Service	0.2	3		2		2		1	
Durability / Wear	0.8	2		2		2		3	
Performance	30%	4.1	1.23	3.4	1.02	2.1	0.63	3	0.9
Pinch Force	0.3	4		4		3		4	
Size	0.6	4		3		2		3	
Hand weight	0.1	5		4		4		3	
Total Score			4.08		3.39		3.26		2.25

Fig. E-7: Compliant Actuation Mechanism Scoring Matrix (Jamie)

Mike - Non-Compliant Actuation Mechanisms Scoring

Selectrion Criteria	Weight	Linkage Rating (1-5)	Linkage Weighted Score	Gears Rating (1-5)	Gears Weighted Score	Tendon Rating (1-5)	Tendon Weighted Score
Manufacturability	20%	4	0.8	3	0.6	5	1
Local	0.7	4		3		5	
India	0.3	4		3		5	
Feasability	30%	2.1	0.63	1.1	0.33	4.9	1.47
Simplicity	0.9	2		1		5	
Overall Cost	0.1	3		2		4	
Robustness	20%	4.6	0.92	1.8	0.36	2.2	0.44
Maintinence / Service	0.2	3		1		3	
Durability / Wear	0.8	5		2		2	
Performance	30%	2.7	0.81	2.3	0.69	3.3	0.99
Pinch Force	0.3	4		5		1	
Size	0.6	2		1		5	
Hand weight	0.1	3		2		5	
Total Score			3.16		1.98		3.9

Fig. E-8: Non-Compliant Actuation Mechanism Scoring Matrix (Mike)

Evan - Non-Compliant Actuation Mechanisms Scoring

Selectrion Criteria	Weight	Linkage Rating (1-5)	Linkage Weighted Score	Gears Rating (1-5)	Gears Weighted Score	Tendon Rating (1-5)	Tendon Weighted Score
Manufacturability	20%	3	0.6	2.7	0.54	4	0.8
Local	0.7	3		3		4	
India	0.3	3		2		4	
Feasability	30%	3	0.9	2	0.6	3.1	0.93
Simplicity	0.9	3		2		3	
Overall Cost	0.1	3		2		4	
Robustness	20%	4.6	0.92	2	0.4	2.2	0.44
Maintinence / Service	0.2	3		2		3	
Durability / Wear	0.8	5		2		2	
Performance	30%	2.6	0.78	3.3	0.99	3	0.9
Pinch force	0.3	4		4		2	
Size	0.6	2		3		4	
Hand weight	0.1	2		3		4	
Total Score			3.2		2.53		3.07

Fig. E-9: Non-Compliant Actuation Mechanism Scoring Matrix (Evan)

Jamie - Non-Compliant Actuation Mechanisms Scoring

Selectrion Criteria	Weight	Linkage Rating (1-5)	Linkage Weighted Score	Gears Rating (1-5)	Gears Weighted Score	Tendon Rating (1-5)	Tendon Weighted Score
Manufacturability	20%	3.3	0.66	2.3	0.46	4.7	0.94
Local	0.7	3		2		5	
India	0.3	4		3		4	
Feasability	30%	1.2	0.36	1.9	0.57	4	1.2
Simplicity	0.9	1		2		4	
Overall Cost	0.1	3		1		4	
Robustness	20%	4.8	0.96	2.6	0.52	2	0.4
Maintinence / Service	0.2	4		1		2	
Durability / Wear	0.8	5		3		2	
Performance	30%	2	0.6	2.9	0.87	3.3	0.99
Pinch Force	0.3	4		5		3	
Size	0.6	1		2		4	
Hand weight	0.1	2		2		5	
Total Score			2.58		2.42		3.53

Fig. E-10: Non-Compliant Actuation Mechanism Scoring Matrix (Jamie)

Selectrion Criteria	Weight	Myoelectrics Rating (1-5)	Myoelectrics Weighted Score	Mechanomyogram Rating (1-5)	Mechanomyogram Weighted Score	Resistive Fabrics Rating (1-5)	Resistive Fabrics Weighted Score
Consistency	30%	3.7	1.11	1	0.3	4.4	1.32
Reliability of intended actuation	0.70	4		1		5	
Susceptibility to accidental actuation	0.30	3		1		3	
Physical Profile	40%	3.25	1.3	3.2	1.28	2.25	0.9
Noticeability/Anthropomorphism	0.50	3		3		2	
Fit to arm and comfort	0.15	1		4		2	
Physical constraints to body	0.20	5		4		1	
User intuition	0.15	4		2		5	
Robustness	15%	2	0.3	3	0.45	2.5	0.375
Maintanance / Service	0.50	2		3		2	
Durability / Wear	0.50	2		3		3	
Informatin Acquisition	15%	2.9	0.435	1	0.15	3.3	0.495
Filtering Needed	0.30	3		1		3	
Processing Load	0.40	2		1		3	
Technical Feasibility	0.30	4		1		4	
Total Score			3.145		2.18		3.09
Rank			1		3		2

Fig. E-11: Biointerface Scoring Matrix

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Appendix F: Initial BMVSS Discussions

The following information describes detailed notes of the team's first interactions with BMVSS. Takeaways from these meetings were instrumental in guiding the design process.

Meeting Minutes from June 14th Prosthetic Hand Conference Call

Dr. Kitts, Dr. Asuri, Jamie Ferris, JP Norman, Shiyin Lim

June 14, 2018

- Body-Powered vs. Myoelectric
  - There is a need for both, with different users in mind.
    - Grip strength and robust design for rural population
    - Finework, passive limb functionality for white collar workers, students
  - They are working with other groups on body-powered prostheses.
  - Majority of prostheses are BP because they have lower maintenance than myoelectric (think batteries and sensors), they are cheaper, and they provide a better understanding of grip when used in labor-intensive situations. Typically, BP prostheses are for individuals who do not need the prosthesis to complete fine motor skills.
  - Problems with myoelectrics include sweat making the sensors difficult to use, as well as inability to apply adequate force.
  - BP is easier to use because the muscles being utilized are large (shoulder muscles) whereas the muscles being used in myoelectrics ar smaller and harder to control
  - For bilateral amputees, try to give at least one myoelectric prosthetic.
  - Takes 1-3 days to get used to myoelectric control (young, fit, smart people)

- Design Notes
  - Voluntary opening preferred design (closed at rest--less energy, cosmetically superior)
  - Hooks have 100% rejection rate in India, even if free
  - Grip strength vs. Speed determinations, switching function?
    - The speed of response is often limited by an additional glove
  - Visibility of object is important since sensory feedback is limited

- Cost
  - Body Powered ≈ $70 Transradial, $90 Transhumeral
  - Myoelectric ≈ $2000 Transradial, >$3500 at higher end
  - Government cap of ≈$150 per limb to NGOs and other orgs. Assisting disabled
  - Don't want to focus project on being cost driven. Aim for $150 but if it's above $250 it is fine

- Aim for manufacturing in India
  - Determine manufacturing options and prices for sourced parts
  - Current brands purchased are Ottoboch (German) and Blatchford (U.S.)

- Information needed from Dr. Pooja Mukul
  - Surveys:
    - Upper Extremity Functional Status
    - OPUS
    - DASH
  - Spec sheets for currently used myoelectrics

Meeting Minutes from Oct. 10th Prosthetic Hand Conference Call

Dr. Pooja Mukul, Dr. Chris Kitts, Dr. Prashanth Asuri, John Paul Norman, Jamie Ferris, Evan Misuraca, Shiyin Lim, and Mira Diwan

10 October 2018

Purpose:
- Update Dr. Pooja Mukul on project progress
- Receive technical feedback on the design direction
- Receive additional input on the target user and how different aspects of the design might be received

Follow Up:
- Dr. Pooja Mukul will provide:
  - All available information on commercial prosthesis costs
  - Any previous survey data collected by/for the Stanford team
  - Send prosthesis and glove to SCU when a decision is reached on which prosthesis will be the most helpful .
- The SCU team will:
  - Choose which prosthesis we would like to have sent to SCU for reference
    - Consider the number of fingers, the movement of the thumb,and the number of EMG sensors
    - The hand should come with a glove
  - Provide an update on the advances in cost reduction
  - Run an experiment restricting use of the non-dominant hand for a day
  - Speak to the veterans association about surveying urban amputees

Technical update
There have been three primary areas of focus within the summer work:
1. Reduction of prosthesis cost

2. Increase of anthropomorphism
3. Increase of both active and passive control.

Our hope is that we can create room in the prosthesis budget for inclusion of additional functionality and anthropomorphism without sacrificing the integrity and durability of the device.

Additional detail can be found in the memo sent at the end of the summer.

Technical questions and feedback from Dr. Pooja Mukul

- The project should not ultimately be cost driven. The function and durability of the device is paramount to ensuring the prostheses' success.
- The hand we currently have is in fact an Ottobock SensorHand and costs approximately $4,700. In light of this, $400 to $500 can be considered low cost for a prosthesis.
- Purely cosmetic hands can be very expensive ($840 to $2,100) due to the detail of anthropomorphism, but Dr. Pooja provides filled latex gloves as a cosmetic hand for about $8.
- Prostheses should be built to endure 1.5 million cycles.
- Be sure to use 3D printed parts only in prototyping and not in the final design.
- Focus on simple, basic functionality rather than getting caught up in detailed motion.
- Make sure that initial customer trails and feedback instill confidence in the device.
- Voluntary opening is prefered over voluntary closing as it looks more natural, requires only input to open and grab, and decreases the pinch force requirements.
- Single or double site EMGs are both options. The single site EMGs might be a way to reduce cost as long as the inputs can be translated into open/close motion.
- Hand pronation and supination is not highly utilized by prosthesis users. Tripod grip is the most common and useful grip.

- While prosthesis companies usually manufacture their own gloves, they are of standard size and interchangeable. The hand should fit within standard latex hand coverings since we won't be able to manufacture just ten of a custom glove to try.
- Overall, do not try to design the perfect hand. Recognize our limitations and aim for an excellent design of a simple hand.

Input on customer needs and empathy
- It is possible to receive customer input via surveys. We should let Dr. Pooja Mukul know if we have the need. We can also get previous data that Stanford collected from Dr. Pooja Mukul.
- While there is a large population of farmers with amputees, myoelectric is likely not the best fit for them and therefore we should not design for that user base.
- The target user is:
    - Urban
    - Young and healthy
    - White collar, industrial workers
- This will require the device to be robust and functional in addition to anthropomorphic.
- Hand dominance will switch after about 3 to 4 months, so we should design for use of the prosthesis as the non-dominant hand.
- Prosthesis will be the supporting hand! Picture carrying items, assisting in writing, packaging in industry, and everything else that a non-dominant hand helps with.
- Because only 5 to 15% of Indians have access to prostheses, we are aiming to outfit each person with a single prosthesis. They will likely not have multiple to choose between for different functions unless the cheat the system.
- Remember that hook prostheses and other non-anthropomorphic prostheses will always be rejected by Indian amputees, even if offered for free.

Questions for Patients and Others

Questions For Patients

1. How long have you been an amputee?
2. Walk us through your daily routine. What are common actions you perform throughout the day?
3. What activities do you have the hardest time doing without the use of both hands?
4. Please provide information on your current prosthesis and past prostheses (if applicable)
   a. What type? How much did it cost?
   b. What did you like and dislike most about it?
   c. How long did they last and was that a problem? What was the maintenance like?
   d. How much of the time did you wear it?
      i. In what situations did you wear it? In what situations did you leave it off?
5. What is your biggest desire from the prosthesis? (comfort, function, aesthetic, etc)
6. How much are you willing to do to maintain a prosthesis?

Questions for Those Interfacing with Patients (Doctors, Prosthetists, etc.)

1. Within the following domains, identify the key needs of your customers. How do these areas stack up against each other (which considerations are priorities)?
   a. Ruggedness
   b. Weight
   c. Affordability
   d. Simplicity of Interface
   e. Simplicity of Usage
   f. Functional Adaptability
2. Activities of Daily Living

a. Are there specific ADLs that patients note having a difficult time with?

b. What ADLs do the patient's prosthesis play a substantial role in?

3. Can you provide access to any additional cost / consumer information data?

Appendix G: Code

The following codes are written in Arduino C. Pin numbers for the motor and flex sensor should be updated based on how the circuit is wired.

Single Sensor Threshold Control

```
//Threshold Control

//Include Libraries
#include <Servo.h>

//Macro Definitions
#define MOTOR_PIN 6 //Motor Digital Output
#define FLEX_PIN 0 //Flex Sensor Analog Input

//Servo Declaration
Servo LA;

//Global Variables
const float threshold = 35000;
const int slopeTrigger = 40;
const int delayTime = 200;
const int windowTime = 500;
const float VCC = 4.98;
const float R_DIV = 45600.0;
const float STRAIGHT_RESISTANCE = 24300.0;
const float BEND_RESISTANCE = 90000.0;
float flexV, flexR1, flexR2, slope;
int flexADC;
int tN;
int tP;
```

```
int printer;
int nPrint;
int tPrint;
bool NegSlope = false;
bool PosSlope = false;
bool hand_open;

void setup() {
  Serial.begin(9600); //Serial Monitor For Debugging
  pinMode(FLEX_PIN, INPUT);
  pinMode(LED_BUILTIN, OUTPUT);
  LA.attach(MOTOR_PIN,2000,1000); //Attach Motor
  LA.writeMicroseconds(554); //Close Motor

  //Configure Initial flexR2 value
  flexADC = analogRead(FLEX_PIN);
  flexV = flexADC * VCC / 1023.0;
  flexR2 = R_DIV * ((VCC / flexV) - 1.0);
  delay(delayTime);

  //Track state
  hand_open = false;
}

void loop() {

  flexR1 = flexR2;
  flexADC = analogRead(FLEX_PIN);
  flexV = flexADC * VCC / 1023.0;
  flexR2 = R_DIV * ((VCC / flexV) - 1.0);
  slope = (flexR2-flexR1)/delayTime;
  //Serial.println(slope);
```

```
  Serial.println(flexR2);
  if(flexR2 > threshold)
  {
    //Serial.println("trigger");
    if(hand_open){
      for (int i = 1450; i >= 554; i--) {
        LA.writeMicroseconds(i);
      }
      hand_open = false;
    }
    else{
      for (int i = 554; i <= 1450; i++) {
        LA.writeMicroseconds(i);
      }
      hand_open = true;
    }
    PosSlope = false;
    NegSlope = false;
    delay(1000);
  }
  delay(delayTime);
}
```

Single Sensor Derivative Control

```
//Slope Detection

//Include Libraries
#include <Servo.h>
```

```
//Macro Definitions
#define MOTOR_PIN 3 //Motor Digital Output
#define FLEX_PIN 0 //Flex Sensor Analog Input

//Servo Declaration
Servo LA;

//Global Variables
const int slopeTrigger = 40;
const int delayTime = 200;
const int windowTime = 500;
const float VCC = 4.98;
const float R_DIV = 45600.0;
const float STRAIGHT_RESISTANCE = 24300.0;
const float BEND_RESISTANCE = 90000.0;
float flexV, flexR1, flexR2, slope;
int flexADC;
int tN;
int tP;
int printer;
int nPrint;
int tPrint;
bool NegSlope = false;
bool PosSlope = false;
bool hand_open;

void setup() {
  //Serial.begin(9600); //Serial Monitor For Debugging
  pinMode(FLEX_PIN, INPUT);
  pinMode(LED_BUILTIN, OUTPUT);
  LA.attach(MOTOR_PIN,2000,1000); //Attach Motor
  LA.writeMicroseconds(2400); //Close Motor
```

```
  //Convert to a resistance value (not necessary)
  flexADC = analogRead(FLEX_PIN);
  flexV = flexADC * VCC / 1023.0;
  flexR2 = R_DIV * ((VCC / flexV) - 1.0);
  delay(delayTime);


  //Track state
  hand_open = false;
}


void loop() {

  flexR1 = flexR2;
  flexADC = analogRead(FLEX_PIN);
  flexV = flexADC * VCC / 1023.0;
  flexR2 = R_DIV * ((VCC / flexV) - 1.0);
  slope = (flexR2-flexR1)/delayTime;



  if(slope < -slopeTrigger)
  {
    NegSlope = true;
    tN = millis();
  }
  if(slope > slopeTrigger)
  {
    PosSlope = true;
    tP = millis();
  }


  nPrint = (millis()-tN);
```

```
if(nPrint > windowTime)

{

  NegSlope = false;

}

tPrint = (millis()-tP);

if(tPrint > windowTime)

{

  PosSlope = false;

}


if(NegSlope == true && PosSlope == true)

{

  Serial.println("trigger");

  if(hand_open){

    for (int i = 1450; i >= 554; i--) {

      LA.writeMicroseconds(i);

    }

    hand_open = false;

  }

  else{

    for (int i = 554; i <= 1450; i++) {

      LA.writeMicroseconds(i);

    }

    hand_open = true;

  }

  PosSlope = false;

  NegSlope = false;

  delay(1600);

}

delay(delayTime);

}
```

Two Sensor Clutch Threshold Control

```
//V2 Slope Detection


//Include Libraries
#include <Servo.h>


//Macro Definitions
#define MOTOR_PIN 3 //Motor Digital Output
#define FLEX_PIN 0 //Flex Sensor Analog Input
#define FLEX_PIN_ELBOW 3 //Flex Sensor Input


//Servo Declaration
Servo LA;


//Global Variables
const int slopeTrigger = 125;
const float elbowTrigger = 120000;
const int delayTime = 200;
const int windowTime = 500;
const float VCC = 4.98;
const float R_DIV = 45600.0;
const float STRAIGHT_RESISTANCE = 24300.0;
const float BEND_RESISTANCE = 90000.0;
float flexV, flexR1, flexR2, slope, flexV_Elbow, flexR_Elbow;
int flexADC;
int flexADC_Elbow;
int tN;
int tP;
int printer;
int nPrint;
int tPrint;
```

```
bool NegSlope = false;
bool PosSlope = false;
bool clutch = false;
bool hand_open = false;

void setup() {
  Serial.begin(9600); //Serial Monitor For Debugging
  pinMode(FLEX_PIN, INPUT);
  pinMode(FLEX_PIN_ELBOW, INPUT);
  LA.attach(MOTOR_PIN,2000,1000); //Attach Motor
  LA.writeMicroseconds(554); //Close Motor

  //Configure Initial flexR2 value
  flexADC = analogRead(FLEX_PIN);
  flexV = flexADC * VCC / 1023.0;
  flexR2 = R_DIV * ((VCC / flexV) - 1.0);
  delay(delayTime);

  //Track state
  //hand_open = false;
}

void loop() {

  /////////////////////////////////////////////////////////////

  // Read shoulder flex sensor values

  flexR1 = flexR2;
  flexADC = analogRead(FLEX_PIN);
  flexV = flexADC * VCC / 1023.0;
  flexR2 = R_DIV * ((VCC / flexV) - 1.0);
```

```
slope = (flexR2-flexR1)/delayTime;

// Read elbow flex sensor values

flexADC_Elbow = analogRead(FLEX_PIN_ELBOW);
flexV_Elbow = flexADC_Elbow * VCC / 1023.0;
flexR_Elbow = R_DIV * ((VCC / flexV_Elbow) - 1.0);


//////////////////////////////////////////////////////////////

// flip clutch booleon based on elbow trigger

if (flexR_Elbow > elbowTrigger){

  //Serial.println(flexR_Elbow);

  if (clutch == false){
    clutch = true;
    //Serial.println("Elbow Trigger on");
    delay(1000);
  }
  else if (clutch == true){
    clutch = false;
    //Serial.println("Elbow Trigger off");
    delay(1000);
  }
}

// set negative and positive bools based on slope triggers

if(slope < -slopeTrigger)
{
```

```
    NegSlope = true;

    tN = millis();

  }

  if(slope > slopeTrigger)

  {

    PosSlope = true;

    tP = millis();

  }


  nPrint = (millis()-tN);

  if(nPrint > windowTime)

  {

    NegSlope = false;

  }

  tPrint = (millis()-tP);

  if(tPrint > windowTime)

  {

    PosSlope = false;

  }


  /////////////////////////////////////////////////////////////

  // Actuate hand based on negative and positive and clutch
bools

  if(NegSlope == true && PosSlope == true && clutch == true)

  {


    if(hand_open){

      for (int i = 2400; i >= 554; i--) {

        LA.writeMicroseconds(i);

      }
```

```
        hand_open = false;
      }
      else{
        for (int i = 554; i <= 2400; i++) {
          LA.writeMicroseconds(i);
        }
        hand_open = true;
      }
      PosSlope = false;
      NegSlope = false;
      //clutch = false;


      // delay in order to prevent accidental double triggering
      delay(1600);
    }


  // delay in order to slow loop
  delay(delayTime);
}
```

Appendix H: HELP Hand Business Plan

Executive Summary

This business plan aims to provide a holistic view of a potential venture / investment opportunity centered around the HELP Hand, a human-centered electric prosthetic hand for developing world contexts. Securing funding from investors will allow this project to begin immediately, and ensure that the engineering team can work over the course of the following year to create a market-ready product and manufacturing process and work towards two overarching goals: profit for investors and improved quality of life for amputees in the developing world.

Introduction/Background

Access to quality prosthetics in the developing world is highly limited. HELP Hand fills a gap in the prosthetics market by producing an affordable electrically powered prosthetic hand for the developing world. In the developing world, preventable (accident-based) amputation is far more common, leading to high quantities of amputees in need (See Fig H-1). This is due to higher rates of infections (due to lack of sanitation) and less stringent workplace safety standards [H-10].
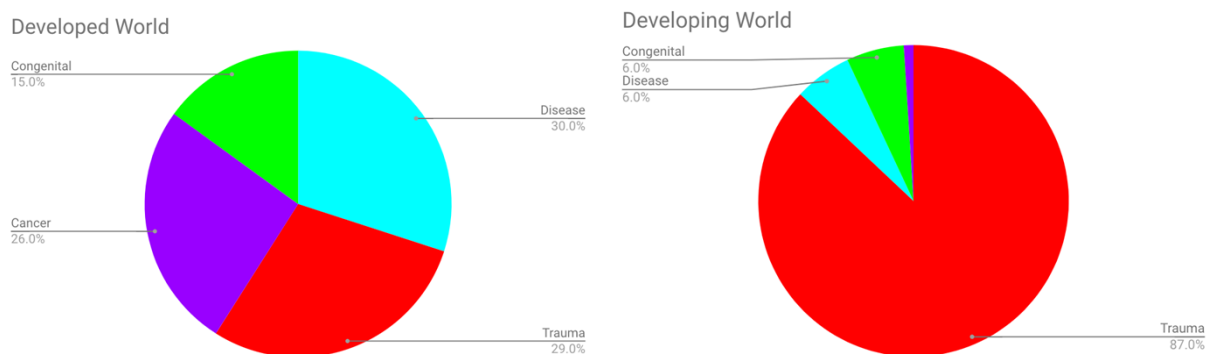
Fig. H-1: Breakdown Of Amputation Cause, Developed World vs. Developing World [H-10]

Due to the financial limitations of these developing populations, currently accessed prosthetic technologies are often uncomfortable and lack both intuitiveness and functionality [H-2]. Electrically powered prosthetic hands allow for a user-friendly biointerface that can create a natural and inviting feel for users. However, existing myoelectric technologies that are commercially available are generally far too expensive for customers in the developing world [H-3].

HELP Hand aims to simplify and reduce the price of this technology such that it can be brought to developing markets. The initial target market will be urban India, with the ability to expand to similar markets in the future. Tackling this problem presents large market opportunity while simultaneously contributing to the social good by enabling amputees to perform their activities of daily living with ease and comfort.

The general plan, which will be outlined in more detailed, is to assemble a team of engineers and project managers to work on improving upon the initial HELP Hand prototype for an entire year. At the end of the first year, we hope to have partnered with an existing network of distribution centers, most likely BMVSS who has been a project partner so far, in order to have our commercial venture launched. This distribution network greatly limits the scope and required investment for the project, and it is mutually beneficial to all parties involved.

Goals/Objectives

Our objective is to bring a low cost electrically powered prosthetic hand that will serve unilateral, transradial amputees through a biointerface to market. The design emphasizes versatility, simplicity, functionality, and manufacturability in India, all while achieving a dramatic cost reduction from the current competition. We seek to obtain 2.5 million dollars of investment to launch a one-year project centered around finalizing a market-ready engineering design and implementing a manufacturing process in India to make this business a reality.

Description of Product

HELP Hand is a mechanical device that fits inside of a prosthetic glove. The product comes with a wearable biointerface, where the user can place sensors into different locations on a shirt and then use different flexures and movements on their body in order to trigger actuation of the mechanical hand. From the outside, HELP Hand is only visible as a prosthetic glove that can open and close.

Potential Markets

As discussed, the initial target market for this product will be urban Indian environments. Electrically powered prosthetics are better suited for white-collar applications (since the grip strength is lower compared to alternative options) [H-5]. As of 2016, India has an estimated population of over 1.32 billion people. 41 Indian cities have over 1,000,000 people, which indicates a high level of urban concentration [H-8]. It is estimated that nearly 0.062% of the population suffers from some type of amputation, resulting in about 800,000 amputees [H-10]. As this product would be targeted at upper-body amputees, it's estimated that we would have a potential customer base of 400,000 individuals. The high regional concentration of people is important as prosthetics must be fitted in fitting centers by prosthetists. Thus, less fitting centers are needed to serve large contingencies of people which gives this product a higher chance of success. Similarly, a large number of people close together, especially with a product like this, allows for a regional expansion model. Currently, there is limited access to prosthetics in India (5-15% of the amputated population has a prosthetic), and the functionality of such prosthetics is unsatisfactory [H-2].

As of 2018, India's GDP is the 116th largest in the world, and at just 7,147 USD, their GDP per Capita is 8 times smaller than in the United States [H-8]. Understanding their economic limitations is critical in finding an appropriate price point and selling strategy for our electric prosthetic hand. The Indian government subsidizes $150 per limb on an amputee to help Non-Government Organizations (NGOs) provide prosthetics to amputees [H-6]. As a result, our product can be sold directly to NGOs in India who

already have the resources in place to fund and distribute prosthetic hands. Accessibility, both in a sense of cost and fitting centers, are critical to the success of our product. Thus, we aim to develop a product and manufacturing process that can be easily implemented into an already existing NGO infrastructure.

One example of an organization like this is Baghwan Mahaveer Viklang Sahayata Samiti, or BMVSS. BMVSS has been a partner in the development of the HELP Hand as a senior design project. Fig. 2-1 illustrates their fitting centers across India, in relation to the population distribution of India.
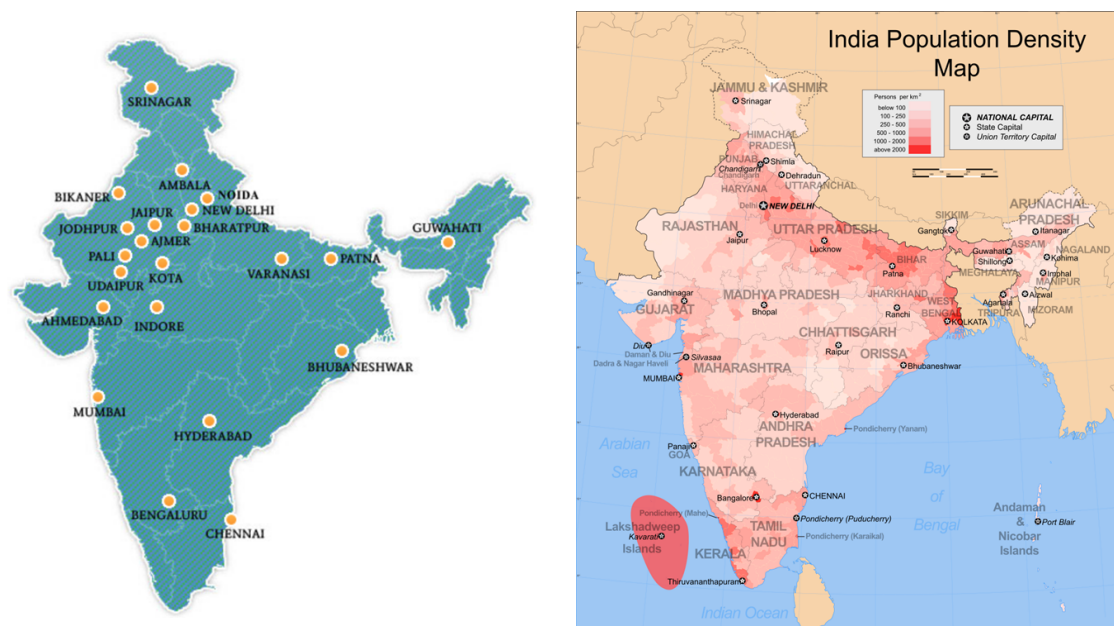
Fig. H-2: BMVSS Fitting Centers [H-7] vs. Indian Population Density [H-7]

With a successful product launch in India, the product could use profits to expand within India or to develop fitting centers and sell directly to customers. Alternatively, the product could be expanded to other developing nations.

Competition

The electrically powered prosthetics market is mostly saturated at two ends of a spectrum: high-end and extremely expensive devices and cheap 3D printed hands that

were created for a design-it-yourself (DIY) purpose. Table H-1 provides an overview of some representative myoelectric hand options.

Table H-1: Summary benchmark data on existing prostheses [H-6]

Prosthesis	Commercially Available?	Cost (USD)	No. Joints	No. Actuators	Weight (lbs)	Grip Force (lbs)
iLimb Quantum	Yes	80,000	11	6	1.10	28.3
Ottobock Michelangelo	Yes	60,000	6	2	0.93	15.7
Taska	Yes	35,000	9	6	Unknown	Unknown
Ottobock SensorHand	Yes	4,700	3	1	1.01	22.5
Openbionics Hero Arm	No	2,000	11	5	2.00	Unknown
Dextrus	No	1,100	14	6	1.00	Unknown
Tact	No	250	11	6	0.77	3.6
Exii Hackberry	No	200	14	3	1.43	Unknown

As illustrated by the table, most myoelectric prosthetic options have many joints and actuators. The quantity and quality of actuators generally drives the high cost of these prosthetic devices. The simplest commercially available options that NGOs are currently providing to limited amputees are priced at over $4000 (the Ottobock Sensor Hand). The NGOs are not able to provide the lower-cost options as they are not of high enough quality or well-designed for manufacturing. 3D printed plastics, which make up many of the lower cost options, are generally characterized by low quality and poor durability and are not suitable for mass manufacturability.

Without affordable, accessible and durable myoelectric technology, urban, white-collar Indians are stuck with a choice between budget breaking myoelectric devices and bulky body powered prosthetics designed for a different set of users.

Sales/Marketing

Sales and marketing would not be particularly important given the business plan of the HELP Hand. Since our goal would be to reach customers through an existing network of prosthetics distributor, the team only needs to market and sell to the distributors themself rather than reaching individual consumers.

In order to best market to these existing distributors, HELP Hand must improve substantially upon their existing options as outlined in the "Competition" section. The main marketing strategy will be to emphasize how the HELP Hand has achieved a dramatic cost reduction from the current competition with initial prototypes, while it still has a wide range of functionality and versatility.

Manufacturing

Hiring of a manufacturing engineering to implement a manufacturing process over the following year will be an important step to bringing the HELP Hand to market. Manufacturing will take place in India, in partnership with an existing distribution network. When expansion becomes appropriate, there will be the potential to contract with external factories in India to ramp up production. Inventory necessary should be reasonably minimal, but will be dependent on the process.

Product Cost

Completion of this venture requires support from investors. A one time investment of 2.5 million dollars is required for personnel and material over the first two years. By the second year, we intend to be turning a profit and begin paying off this debt. Table 3-2 overviews the personnel needed to ensure the production of a market-ready product in one year.

Table H-2: Recurring annual labor costs

Personnel	Role	Annual Loaded Salary
Mechanical Engineer	Mechanism design	$240,000.00
Electrical Engineer	Sensor calibration and integration, signal processing, circuitry, motor selection, battery selection	$240,000.00
Manufacturing Engineer	Design manufacturing process, work with mechanical and electrical engineer on part selection	$200,000.00
FDA Approval Consultant	Achieve FDA Approval for Class Medical Device	$240,000.00
Project Manager	Oversee project, interface with outside NGOs, manage business aspects	$200,000.00
Total		$1.12M

Table 3-3 overviews the cost of material and manufacturing (For prototyping) that will be needed in the first year. This cost accounts for many iterations and prototypes leading up to a final product in the end of the year. Product development will continue year-to-year, and even as it slows down, other variable costs will be incorporated into the project. Therefore this figure will be repeated in the annual budget.

Table H-3: Material / Prototyping Costs (Annual But Variable)

Expense	Description	Annual Projected Cost
Actuation Mechanism	Motors, raw material (metal, plastics), fasteners, other mechanical parts	$10,000.00
Electrical Hardware	Batteries, microcontrollers, basic components, EMGs, other sensors	$10,000.00
Hand Body	Raw material (metal, plastics)	$5,000.00

Machining	Outsource machining to prototyping shops to increased speed and iteration of prototyping	$20,000.00
Travel & Lodging	Test Prototypes in India and Work on Manufacturing Prototypes	$60,000
Total		$105,000.00

Altogether, the project aims to sell 2,500 hands annually at an $800 profit per hand for a $2.1M annual income in order to pay back investors in a timely fashion. **This would put the price point of the hand around $1,400 assuming a $300 parts cost and $300 manufacturing cost associated with each hand.** With a customer base of nearly 400,000 individuals, only 0.6% of potential customers would be reached per year. This indicates that there would be lots of opportunity for growth and expansion without the need to worry about market saturation. It is our hope that this product would yield a returning customer base such that market potential would never be an issue.

In addition to the initial investment, we have use for investors with resources and connections in India who can help create relationships with NGOs and infrastructure to distribute and fit prosthetic hands.

Service or Warranties

HELP Hand is rated to last for over one million cycles (3 years of product life in the prosthetic hand space). The existing distribution networks that we will partner with as a part of this business launch will help in the area of service. HELP Hand will be incorporated into their existing service systems.

Return on Investment

Based on expected profits from hand sales each year, an investment of $2.5M will be paid back in the 6th year after it is made. The 2.5M in full investment comes with 10% stake in the company, and the investor will begin to make profits accordingly (see Table

3-4). The investors for this venture will benefit from both fiscal profit and being responsible for a vast humanitarian effort.

Table H-4: Financial forecast in millions USD

Year	Profit From Hand Sales ($M)	Expenses ($M)	Annual Net ($M)	Overall Net ($M)
1	0	1.23	-1.23	-1.23
2	2	1.23	0.77	-0.46
3	2	1.23	0.77	0.31
4	2	1.23	0.77	1.00
5	2	1.23	0.77	1.85
6	2	1.23	0.77	2.62*

(*Investors paid back in full during year 6)

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Appendix I: Undergraduate Programs Funding Request

Undergraduate Program Funding - Project Proposal

HELP Hand - Human-centered Electric Prosthetic Hand

Table I-1: Team Members and Roles

Team Member	Department	Role
Prashanth Asuri	BIOE	Faculty Advisor
Chris Kitts	MECH	Faculty Advisor
Jamie Ferris	MECH	Undergraduate Student
Shiyin Lim	BIOE	Undergraduate Student
Michael Mehta	MECH	Undergraduate Student (Primary Student Contact)
Evan Misuraca	MECH	Undergraduate Student

Many amputees lack access to prostheses and are therefore unable to sustain employment. Additionally, the amputation presents them with a social stigma that leads to discrimination and even ostracization. Through iterative design and prototyping and interdisciplinary collaboration, our team will build an anthropomorphic electrically powered, accessible prosthetic hand. This solution aims to empower, enable and encourage amputees in India to carry out the activities of daily life needed to live their lives with minimal impairment.

This project was brought to Santa Clara University by Baghwan Mahaveer Viklang Sahayata Samiti (BMVSS), a Jaipur-based non-profit organization that provides free prosthetics to people across the developing world (primarily India). They have had enormous success with their lower body prosthetic, the Jaipur Foot, and to build off this success they are looking to provide a frugal, functional, durable and manufacturable

prosthetic hand. We will be working directly towards this goal for our senior design project. BMVSS provides the infrastructure and support that our team needs to make an impact in the region. Over the course of the project, we will focus on selecting the right materials, mechanisms, actuators, electrical components, bio-interface and aesthetics necessary to produce a human-centered product in-line with BMVSS's vision and the needs of their users.

University Funding Sources

This team has not applied to any other internal university funding sources.

External Project Sponsors / Partners

This project is sponsored by BMVSS. BMVSS is the creator and provider of the Jaipur Foot, a frugal prosthetic foot, and has fitted over 1.75 million people (mostly in India) with a lower limb prosthesis. BMVSS possess a strong customer empathy that will help guide our design decisions. Our team, under the guidance of Dr. Kitts, Director of the Robotic Systems Laboratory, and Dr. Asuri, Director of BioInnovation and Design Lab, will interface with BMVSS once a month over the course of the next year. Our main point of contact will be Dr. Pooja Mukul, Rehabilitation Physician and Clinical Director of Jaipur Foot Rehabilitation Center. BMVSS has allocated significant funds for the larger prosthetic hand project. However, the overall project scope has multiple deliverables, including multiple graduate student capstone projects. As a result, just $1,500.00 of BMVSS's total funding will be allocated to our senior design team for a functional prototype.

Budget

We would like to request Undergraduate Programs funding for the following project material costs. We are expecting to use many of each component as we construct numerous prototypes and iterate on our mechanism design concepts. All cost estimates are rough (since specific part requirements are not yet known) but are based off on listed prices of general items within the category.

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Table I-2: Funding Request Breakdown

Component	Justification	Cost
Actuation / Mechanism		
Motors	We plan to iterate through multiple sizes, types and power ratings of motors throughout our design process.	$500.00
Raw Material - Metal	Machine linkages and other small components to help build mechanisms to actuate hand and differentiate motor force.	$300.00
Fasteners	May include nuts, bolts, screws, rivets, etc. May be used within hand actuation mechanism.	$200.00
Mechanical Parts Misc.	May include springs, pulleys, cord and other mechanical parts used to build hand actuation mechanism	$300.00
Hand Body		
Hand Body	Construction of the exterior body of the hand. We expect to make many iterations with many different material concepts.	$600.00
Glove	Anthropomorphic & covers prosthesis to hide mechanisms.	$200.00
Electric Components		
Batteries	Different batteries may be needed for different iterations. Cost will vary greatly based on requirements for voltage, battery life and rechargeability.	$300.00
Microcontrollers	Physically small microcontroller. Processing power TBD based on required inputs. Specific model to be determined once more mechanism design has been completed. We will begin prototyping with accessible arduinos and then transfer to the final control schema.	$300.00
Basic Electronic Components	Resistors, capacitors, inductors, wires, op-amps, etc.	$200.00
Sensors	Force sensitive resistors, accelerometers, thermistors	$200.00
Myoelectric Components	Used for biointerface. Wet electrodes, dry electrodes, conductive fabric, textile EMGs, Myoware control boards.	$500.00
Total		$3,600.00

A grant from BMVSS has allocated $1,500 of funding towards a functional prototype for our project. However, we wish to explore advanced sensing options that will improve the interface of our hand. The budget constructed below is based off the full scope we wish to pursue, beyond the baseline requirements BMVSS has asked us to meet. Subtracting the BMVSS funding allocation, the total requested amount is **$2,100.00**

Xilinx

Additional funding (beyond the amount requested above) will allow our team to explore more design options through increased prototype materials and faster prototype production. In order to ensure the best possible outcome in the final design, we intend to explore as many design options as possible. This requires both more materials and more time. By outsourcing prototype manufacturing to machine shops we can reduce the time used to manufacture prototypes, thereby giving us the ability to produce more prototypes within our given time frame. Additionally, the complex geometries needed in order to machine a prosthetic hand would be very difficult to create in the SCU Machine Shop. Funding to support outsourcing some of the machining work will greatly broaden our ability to make the hand as human-like as possible.

With limited funding, we may pursue only one or two designs with a couple of different materials. However, with additional funding we can work to simultaneously design and prototype various actuation mechanisms and biointerfaces such that we ensure the best possible outcome in the final design. Specifically, additional funding will allow us to purchase and prototype with more motors, sensors, electrical systems, and bio-interfaces in order to find the best combination. Ultimately, greater funding upfront can help us deliver a product with lower end cost and higher functionality for the user.

Our team recognizes that acceptance of any funds from Undergraduate Programs commits us to presenting our project in a poster session at Family Weekend in February, Preview Weekend in April and the Spring Engineering Education Days (SEEDs) program, also in April.

Our faculty advisors acknowledge that they have reviewed and support the team's proposal for Engineering Undergraduate Programs Senior Design funding.

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Appendix J: Safety Report

HELP Hand
Jamie Ferris, Michael Mehta, Evan Misuraca

This document serves to outline and detail any potential safety concerns that this project may encounter. Safety is paramount in any engineering discipline, however it is even more important when considering our use case and intention for human-centered design. The following safety review will be comprehensive and ensure that the project meets all requirements and guidelines. All team members and faculty advisors will be made aware of the Safety Review and be required to sign off on it.

This safety review concerns the scope of the senior design project and will not be wholly inclusive of the long term goals associated with this project and the University's partnership with BMVSS. We will still, of course, keep the big picture in mind and will be aware of how current design and manufacturing processes associated with our project will influence safety later on when this overall project is implemented.

Six categories have been designated for this safety review, and while some safety concerns will overlap, we aim to highlight the particular concerns associated with each category. The project and its scope will continue to be fluid throughout the next 8 months, and thus any additional safety concerns that may arise will need to be noted and then further documented.

Manufacturing

Manufacturing the HELP Hand includes both short term and long term safety concerns. For this particular document, we will focus on the safety concerns relevant to the manufacturing that will occur over the duration of the senior design year. This

manufacturing will include subassembly builds, the prototype builds, and also the final project build. As for any case of manufacturing, we will have to ensure that our manufacturing process is safe. Safety concerns related to our project include, but are not limited to, proper machine use / material use, and following relevant guidelines. This means that in the early stages of this project (which is currently happening), we will have to design for manufacturability. The following subcategories will provide for a better overall evaluation of safety related to manufacturing our product:

- Machining: The manufacturing process for different prototypes and different subassemblies will vary drastically, but for metal and other solid body parts that can be machined using Santa Clara University's machine shop, appropriate protocols will need to be followed carefully. The MECH 101L safety procedures will be implemented and used and Don MacCubbin will be our main point of contact for subtractive manufacturing using the lathes, mills, and various other tools.

- 3D Printing: The 3D printers available for use in the MakerLab will be a vital asset to the prototyping portion of our project and ideas can be quickly designed and tested. All MakerLab protocol will need to be followed and relevant MakerLab training will need to be conducted. Anne Mahacek will be the main point of contact for any work done in the MakerLab.

- Basic components: It is our hope that most of the parts involved in our project can be purchased and pre-manufactured. Part of this is due to the fact that we want this product to be as easily manufacturable as possible and the other part is safety. Sourcing parts takes the safety concern for manufacturing out of our hands, but means that we will need to be aware of the components' capabilities and limits.

Assembly

Safe assembly of the HELP Hand and all related subcomponents and prototypes will be an undertaking. Once all components have either been sourced or manufactured, they will need to be brought together in a safe and responsible manner. Assembly will largely

take place in the Robotic Systems Laboratory at Santa Clara University. For the RSL, Santa Clara School of Engineering Safety Code will be followed. Should any other area be used for assembly, proper respective safety protocol will be followed. In general, overall guidelines should remain the same and will include the following areas of concern:

- Soldering: Safety protection should be worn and hands should be washed immediately after to protect against led ingestion. Proper protocol will protect against burns, fume inhalation, and ingestion.
- Fasteners: The ratings of all related fasteners will need to be noted and checked against their use / application. This will ensure that no fastener is being used out of spec and will eliminate the concern for fastener failure. Ideally, all fasteners will be sourced from the same place such that we have an idea as the the consistency of quality and
- Adhesives: Safety protection against fumes and damaging chemicals will need to be used. Adhesives are not to be used unless in a well ventilated area with proper fume mitigation techniques (i.e. fume hood, large open space, fan, masks). SuperGlue and epoxy are the only likely adhesives that will be needed. Both of these glues undergo a chemical reaction when being used and thus the safety and materials of the bonding surfaces must be taken into account.
- Lubricants: As our product will involve repetitive movement and actuation, lubrication will be needed. Depending on what lubricant is used, different precautionary measures may need to be taken. As this device will be worn on a daily basis by the consumer, we aim to make the wholistic device as safe as possible and will try to ensure that only topically safe lubricants are used.

Test / Operation

Testing and operating this hand will comprise a large portion of this project, and thus it is our goal to make this stage as safe as possible. Throughout the design and handling process, team members should be concerned with eliminating any sharp edges, checking for pinch points, insuring that the maximum grip strength of the prosthesis is

not of a concerning level, and allowing for easy removal in case of anything going wrong. The following subcategories have been defined to make for a more comprehensive analysis:

- Battery/ Power: The primary area of safety concern for this project will be the power supply. We have yet to determine the voltage of the battery we will use; however, our initial product specifications require that our hand be able to pick up 5 lbs. This warrants a strong motor, and we will need a battery that can supply the necessary current and voltage of our motor. The University mandates that projects which utilize > 50V will need to get prior approval and remain under direct supervision from faculty. We believe that out project will remain under 12V and thus do not anticipate having to get approval. While no current limits are stated, we will attempt to keep currents under 3 amps and will ensure that all high powered wires (to motor) are sheathed. The primary safety concern with the battery will involve short-circuits, water, overheating, and replacing / charging. The first two concerns can be addressed with careful planning and protection of circuitry. This portion of the design process will be triple checked to ensure that both the device and user remain safe. The second two concerns will be addressed with battery location and type of battery. Ideally, the battery compartment will be well ventilated and easily interchangeable. At this point in time, we will be attempting to use a replaceable type of battery (AA, 9V etc…) which pose very little safety concerns.
- Human Interfacing: The bio-interface of this device will need to be not only safe, but also comfortable. Our primary concern with the bio-interface portion of this project is the way in which signals will be detected on the human arm. Electrodes of different types are commonly used and we will need to test / ensure that they are non-irritating and can repeatedly used on any type of customer. There are additional ethical and safety concerns in the use of human testing with the prosthesis. Human testing will provide us with direct feedback from prosthesis users here in the US who share use characteristics with our target clientele in India, but placing the prostheses on a human requires extra concern with the practical safety of the device.

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In order to conduct human testing outside of the walls of the University, we have started the online application process for Santa Clara University Institutional Review Board approval. By starting the IRB approval process through the Office of Research Compliance and Integrity, it is our goal to ensure that research and testing is done to the highest standard. We believe that our project poses minimal risk and thus, believe that we will receive approval with little conflict. Should we encounter any issues with approval, we will seek guidance from the School of Engineering. In order to start the process of IRB approval, all members of the design team are going through CITI training. Further steps to be taken will be provided by the Office of Research Compliance and Integrity once CITI training is complete. As soon as finalized approval paperwork is available, it will be compiled into our final safety briefing in our CDR.

Display

As the components and overall product will be relatively sensitive, we would like to be careful with the amount of interaction that occurs during an opportunity for display. We would, however, like for individuals to be able to see how the device works such that they can experience the actuation mechanism and method of bio-interfacing and not just a static device. We have yet to figure out how to achieve both of these things, but as we continue to design and develop, we will simultaneously have a better idea of how to display our project safely.

Display concerns closely align with test / operations concerns in the categories of power and human interfacing. We will need to have a protocol for when the device is to remain off and for how individuals will be able to interact with it. We do not anticipate any large concerns with regards to display, as a prosthetic device will innately be on display whenever a user is wearing it.

Storage

The team will follow all protocol set out by the School of Engineering at Santa Clara University. Our primary concern with storage directly relates to the battery that will be used. If of the replaceable type, overnight battery storage will not be a problem as long as the circuitry involved is able to protect against overnight battery drain. We will need to include guidelines for allowable temperature ranges and other allowable storage conditions.

Long term storage may result in other issues such as inadequate lubrication and misuse by the user. If stored long term, we will include instructions on how to safely bring the prosthetic back up to operating conditions. This may include proper lubrication and battery replacement techniques, and may also include a reminder on how to apply sensors and control the prosthetic. Our main goal for the safety concern of storage is to ensure that the device can essentially be used at any time.

Disposal

Disposal is not a primary concern for our senior design team as our final product will be a part of a larger and longer term project. All prototypes, subassemblies, and end products will be handed off to the next design team or to others involved in order to maximize forward progress.

Short term disposal of batteries is the only disposal concern that will be applicable to our project. We will follow all guidelines set out by the School of Engineering to ensure safe disposal / recycling of everything used. If the School of Engineering does not have specific guidelines in place for a particular item, we will defer to the City of Santa Clara regulations for disposal.

Summary

As mentioned earlier, other unpredicted safety concerns will likely arise over the course of the project as design decisions are made. Safety will be placed above all other factors throughout senior design, and help will be sought for any complex or concerning cases we might encounter.