

Design and Development of a Myoelectric Transradial Prosthesis

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Abstract

The loss of a limb is a life-changing event and reality for 441,000 transradial amputees in the United States. Limb loss can have substantial physical, social, psychological, and economic consequences. A prototype prosthesis was created that has sophisticated hand functionality, an adjustable and comfortable socket, and a lightweight yet durable design utilizing 3D printing, all available at a reasonable price point. The prosthesis integrated force sensors, servo motors, and a myoelectric means of control so the user may perform activities of daily living. The overall outcome was a prosthesis that met its design requirements, offering increased usability, functionality, and availability.

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1. Introduction

The loss of a limb is a life-changing event and a reality for over 2.1 million people in the United States. Of those 2.1 million, 441,000 are transradial, below the elbow, amputations. Upper limb loss has substantial physical, social, psychological, and economical consequences for an amputee. In order to mitigate these consequences and assist the amputee to return to a state of normalcy. Transradial prosthetics, or artificial hands and wrists, are used to perform daily activities such as eating and dressing. The purpose of transradial prosthetics is to help the amputee function as nearly as well as before.¹

The purpose of these prosthetics hasn't changed; however, innovation in technology has vastly improved their performance. Unfortunately, advanced technology has its price. State-of-the-art prosthetics are extremely expensive at hundreds of thousands of dollars. Even cosmeses, prosthetics made only for aesthetics, although less expensive, are still thousands of dollars.

Innovations in 3D printing, an additive manufacturing process, over the past decade have made 3D printed transradial prosthetics an inexpensive alternative. They are able to provide complex functions at an affordable price. Multiple non-profit organizations have independently formed to create innovative 3D printed transradial prosthetics. There are multiple designs that range in ability and function such as scalability, durability, hand grips, control systems, user inputs, materials, aesthetics, comfort, and cost. Each prosthetic design has its own strengths and weaknesses.

This project identified areas for improvements and strengths of these 3D printed transradial prosthetics. The team combined the strengths of many prostheses with their own innovative ideas to design a 3D printed transradial prosthetic. A prototype prosthesis was created that has sophisticated hand functionality, an adjustable and comfortable socket, and a durable yet lightweight design utilizing 3D Printing, all available at a reasonable price point. The prototype was then evaluated against the required specifications. The subject of this report is the design process, manufacture, and testing of the 3D printed transradial prosthetic.

¹ Advanced Amputee Solutions, 2016

2. Background

In order to create an appropriate design, amputations' frequency, causes, demographics, types, and their negative effects as well as the impact prosthetics have on alleviating these negative effects were investigated. Next, the anatomy and physiology of the forearm and an amputated forearm were explored in order to more easily convey later design intentions. The purpose, components, functions, and general design of modern transradial prostheses are described, and several examples of existing technology are analyzed in the following.

The team's goal involved building upon preexisting research in many areas of prosthetics. Several different prosthetic arm/hand designs were analyzed and their best and worst qualities were recorded. In addition, the more advanced systems of prosthetics such as finger actuation, wrist articulation, the connection between the residual limb and the prosthetic, also known as a socket, and the control system of the entire prosthetic were analyzed as well. The team looked at various methods for implementing each of these systems before making design decisions on their inclusion in the final prototype.

2.1 Amputations and the Goals of Prosthetics

The overall goal of prosthetics is to help normalize amputees. Prosthetics accomplish this goal by returning functions that their lost limb previously provided. For example, a prosthetic leg restores the ability to walk; a prosthetic heart valve replaces a damaged, natural valve and allows for better blood flow in the heart; and a prosthetic arm gives an amputee the ability to once again manipulate their surroundings in a more "normal" fashion.

2.1.1 Amputations and Their Effects

Amputation is the last resort when surgical salvage is not possible. Upper extremity amputations can have substantial physical, psychological, social, and economic consequences for the patient.² Thirty-six percent of amputees living with limb loss suffer from depression.³ Amputees pay over half a million dollars in healthcare costs over their lifetime. In the United States, hospital charges for patients who undergo amputations totaled to \$8.7 billion in 2013.⁴

Surgeons try to mitigate consequences by providing maximum use of the residual limb without a prosthesis and minimizing the known complications of amputation. The ultimate goal of amputation surgery is to provide a sensate limb that can best interact with the patient's environment, with and without a prosthesis.⁵

There are over 2.1 million amputees currently living in the United States. That number is expected to grow to 3.6 million by 2050.⁶ Each year, 185,000 people have an amputation. This equates to 507 people losing a limb each day. The two most common causes of these

² Marchessault, McKay, & Hammert, 2011

³ Advanced Amputee Solutions, 2016

⁴ Ibid

⁵ Marchessault, McKay, & Hammert, 2011

⁶ Advanced Amputee Solutions, 2016

amputations are vascular disease (54%) and trauma (45%).⁷ 46% of amputations, happen between the ages of 45 to 64, however limb loss affects people of all ages, from birth to over 85 years old.

Men are approximately two times more likely to have an amputation than women. Upper limb amputations account for 35% of all amputations.⁸ Of these upper limb amputations, transradial amputations comprise 60%.⁹ This means, nationally, approximately 441,000 people are living with a transradial amputation.

2.1.2 Goal of Prostheses

Prostheses rehabilitate amputees by restoring as much function as possible.

The devices do this by targeting functions that fulfill Activities of Daily Living, or ADLs. ADLs are routine activities that people tend to do every day without needing assistance. There are approximately eight¹⁰ ADLs:

1. Food Preparation
2. Feeding
3. Personal Care
4. Housekeeping
5. Shopping
6. Driving and Transport
7. Leisure
8. Others

For detailed descriptions of these ADLs, including a breakdown of how much time is spent on each task on average, see Appendix C. In upper limb prostheses, the restoration of ADLs is essential, as almost all activities demand the use of one or more hand. Approximately five hours out of the day alone is spent by hands completing these essential activities.¹¹ This amount of time

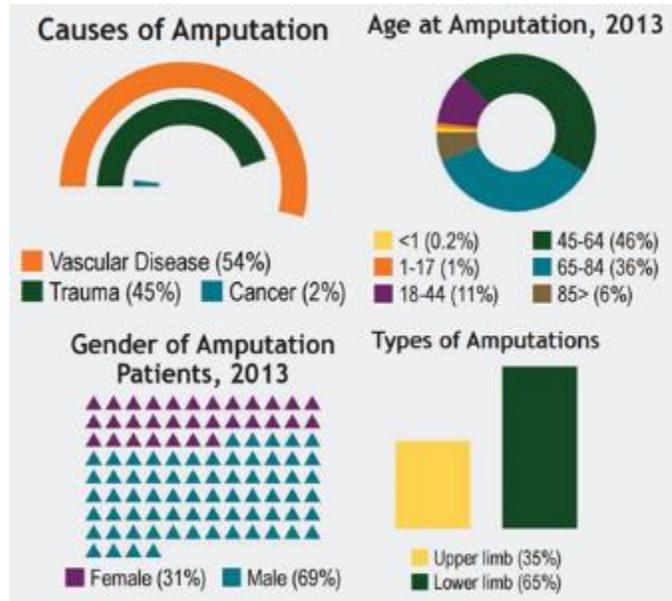


Figure 1: Amputation Statistics



Figure 2: Activities of Daily Living

⁷ Amputee Coalition, 2016

⁸ Ibid

⁹ Ziegler-Graham et. al, 2008

¹⁰ Vergara, M. et al., 226

¹¹ Ibid

does not take into consideration all of the non-essential activities the human hand and arm participate in each day.

2.2 Anatomy and Physiology of the Forearm

It is necessary to understand the basic anatomy and physiology of the human hand in order to successfully design a prosthetic device. Anatomy is the study of structure, and physiology is the study of function. Through the study and understanding of the structure and function of the human hand, it can be mimicked for a better prosthesis.

2.2.1 Anatomical Position

When discussing anatomy and physiology, there are certain assumptions and terminology about the position of the body that are made. The anatomical position of a person is considered to be standing erect with feet flat on the floor and close together, arms at the sides, and the palms and face directed forward as shown in Figure 3. This provides a frame of reference in order to discuss the details of the human body. Table 1 includes the most relevant and commonly used position related terminology and their definitions. For a complete list, see Appendix B.

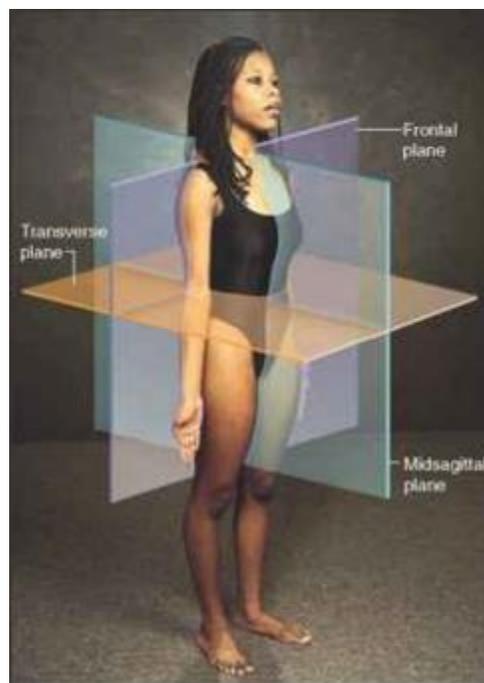


Figure 3: Anatomical position and planes of reference¹²

Table 1: Directional Terms in Human Anatomy

Term	Definition
Sagittal Plane	Passes vertically through the body. Divides the body into right and left sections
Median Plane	Sagittal plane that divides the body into two equal halves
Frontal Plane	Passes vertically through the body, but is perpendicular to the sagittal plane. Divides the body into anterior and posterior sections
Transverse Plane	Passes horizontally through the body. Divides the body into superior and inferior sections
Anterior	Toward the ventral side
Posterior	Toward the dorsal side
Superior	Above
Inferior	Below
Medial	Toward the sagittal or median plane
Lateral	Away from the sagittal or median plane
Proximal	Closer to the point of attachment or origin
Distal	Farther from the point of attachment or origin
Superficial	Closer to the body surface
Deep	Farther from the body surface

2.2.2 Bones

Transradial prostheses replace bones in the hand, wrist, and forearm. Bones provide structure and support that transradial prostheses mimic in the structure and casing. The human

hand is comprised of five different sets of bones, 27 bones overall. The five sets are the carpals, metacarpals, first phalangeal, second phalangeal, and third phalangeal bones. Each finger contains three phalanges, with the exception of the thumb which only has two. The phalanges bones are known as the distal, middle, and proximal phalanges. The thumb only contains the distal and proximal phalange.¹³ There are five metacarpal bones in the palm, which are numbered one through five starting from the thumb moving to the pinky finger. The eight carpal bones make up the wrist and are arranged in two rows. The ulna and radius are the bones of the forearm. The radius bears about 80% of the force on your forearm while the ulna shares the load and minimizes wear and tear. The bones of the hand can be seen in Figure 4.

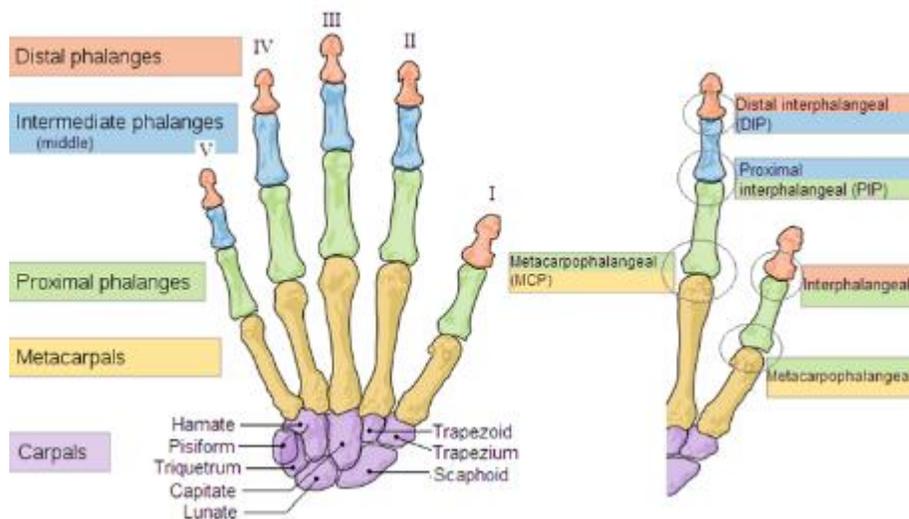


Figure 4: Bones and joints of the hand¹⁴

2.2.3 Joints

Transradial prostheses replace joints in the hand and wrist. Joints provide flexibility, range of motion, and the ability for articulation that transradial prostheses mimic using mechanical joints. Transradial prostheses typically use pins, hinges, and ball joints. The hand contains six different joints, the distal interphalangeal (DIP), proximal interphalangeal (PIP), interphalangeal (IP), metacarpophalangeal (MCP), carpometacarpal (CMC), and radiocarpal (RC) joints. Each digit of the hand contains the DIP, PIP, and MPC which all have ligaments that provide stability. The thumb, however, contains the IP instead of the DIP and PIP as shown in Figure 5. The trapeziometacarpal (TMC) joint at the base of the thumb contains the clearest example of a saddle joint. Saddle joints are biaxial and have greater range of motion than the other phalanx's condylar joints. This range of motion gives humans an opposable thumb. The CMC is between the metacarpals and the carpals. This joint allows the hand to curl and grasp objects. The radiocarpal is the joint between the carpals and the radius and ulna. It enables the wrist to flex and extend.¹⁵

¹³ Saladin, 2012

¹⁴ Brigham and Women's, 2014

¹⁵ Saladin, 2012

2.2.4 Muscles

Transradial prostheses replace muscles in the hand, wrist, and forearm. Muscles provide movement that transradial prostheses mimic using servos, control systems, gears, hinges, and other components. The muscles that control the fingers and thumb lie in the forearm and hand. There are two groups of muscles that comprise the hand and wrist: intrinsic and extrinsic muscles. The intrinsic muscles of the hand provide precise finger movement and allow for each finger to move independently. Intrinsic muscles are separated into four groups: the thenar muscles, that act on the thumb; the hypothenar muscles, that act on the little finger; the lumbrical muscles that help the extension of the IP joints and the flexion of the MCP joints; and the interossei, that allow for abduction and adduction of the fingers as shown in Figure 5.¹⁶

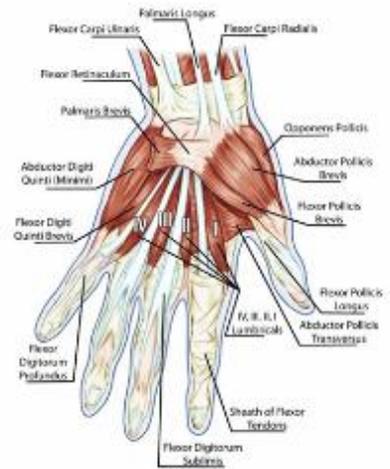


Figure 5: Muscles of the hand¹⁷

The extrinsic muscles of the forearm are larger, longer muscles that run from the forearm to the hand and provide strength. Two important extrinsic muscles are the flexor digitorum profundus (FDP) and the flexor digitorum superficialis (FDS). These muscles are utilized when repetitive work and additional strength are necessary.¹⁸ Figure 5 and Figure 6 show the location of some of these muscles.

2.2.5 Anatomical Change from Transradial Amputations

Transradial amputations change the anatomical structure of the bones, muscles, tendons, and nerves. It is important to understand these changes when designing a transradial prosthetic device. The structure of the residual limb affects the size, length, control, and overall structure of the prosthesis. Each residual limb is unique. This is the biggest challenge of designing and mass producing prostheses. The surgical process and reconstruction of the limb are the key to understanding the differences between residual limbs.

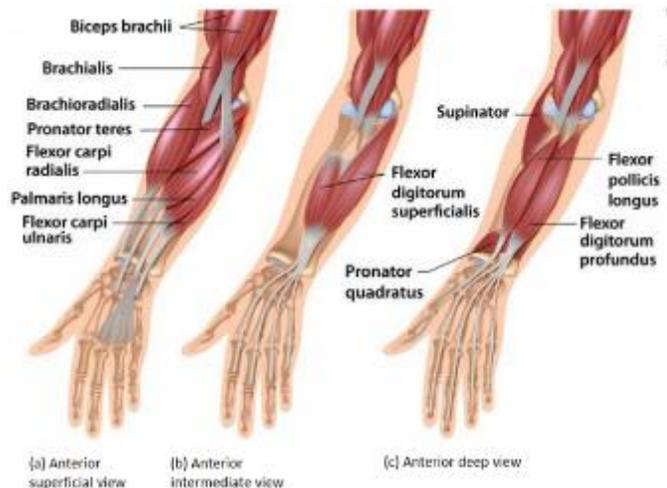


Figure 6: Muscles of the right forearm¹⁹

When the decision is made to amputate an upper limb, preservation of the length and joint function are of

¹⁶ Saladin, 2012

¹⁷ Kelso, 2015

¹⁸ Ibid

¹⁹ Ibid

paramount concern. The upper extremity's interaction with the surroundings depends on the major joints to move the hand through space. An essential part of preservation is ensuring there is not further bone shortening by making sure there is adequate residual soft tissue. The residual soft tissue, particularly muscle, must provide adequate soft tissue coverage of the radius and ulna to allow stump closure.²⁰ Myodesis, anchoring of muscle or tendon to bone, of the deeper forearm muscles to the radius and ulna provides stable bone coverage and prevents bone-on-bone motion that can lead to complications such as fluid collection in the stump.²¹ Myoplasty, muscle to muscle attachment, of the superficial flexor muscles to the extensor muscles must be placed on tension to allow contraction of the muscles after closure. Soft tissue coverage of the radius and ulna with tensioning of the muscles is accomplished with both myodesis and myoplasty.²²



Figure 7: Transradial amputation²³

Myofascial closure, enclosure of the muscle and its sheath of connective tissue, often indicated for dysvascular tissue amputations, is not strong enough for muscle contraction and should be performed only to help contour the remaining muscle bellies to enhance closure. Contractions of the superficial muscle groups are essential to trigger myoelectric prosthetics. Amputation six to eight centimeters proximal to the wrist joint allows for ample muscle coverage; however, ten centimeters proximal is advocated for increased prosthetic options. Forearm amputation at five centimeters distal to the elbow joint is the minimum amount of residual limb necessary for a transradial prosthesis to fit. Although pronosupination, turning of the wrist, is lost with more proximal transradial amputation, preservation of elbow motion is worthwhile. Transfer

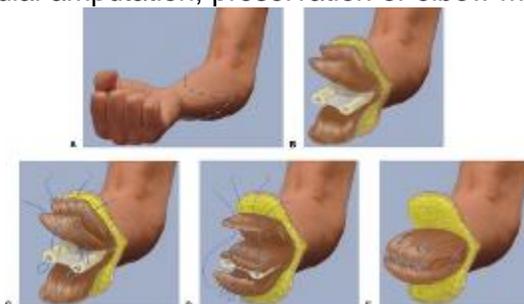


Figure 8: Surgical process of transradial amputation²⁴

²⁰ Marchessault, McKay, & Hammert, 2011

²¹ Singh, Hunter, & Philip, 2007

²² Marchessault, McKay, & Hammert, 2011

²³ Ibid

²⁴ Versalius, n.d.

of the biceps tendon to the ulna should be considered to lessen the risk of flexion contracture with proximal transradial amputations.²⁵

Figure 8 shows a rendition of a transradial amputation. Figure 8-A begins with the incision. Moving from anterior to posterior, Figure 8-B shows the development of superficial and deep flexor mass as well as extensor muscles. Figure 8-C shows myodesis performed with sutures passed through tendinous portions of muscle, through bone tunnels, and passed back through muscle. Figure 8-D shows myodesis of superficial flexors and extensors sutured to each other with some tension. Figure 8-E shows the muscles contoured with myofascial sutures to accommodate tension-free closure.²⁶

2.2.6 Lost Articulation

Transradial prostheses mimic basic functions or types of motion of the human hand. We identified the most important of these for fulfilling ADLs.

- Wrist pronation and supination
- Finger flexion and extension
- Thumb flexion and extension

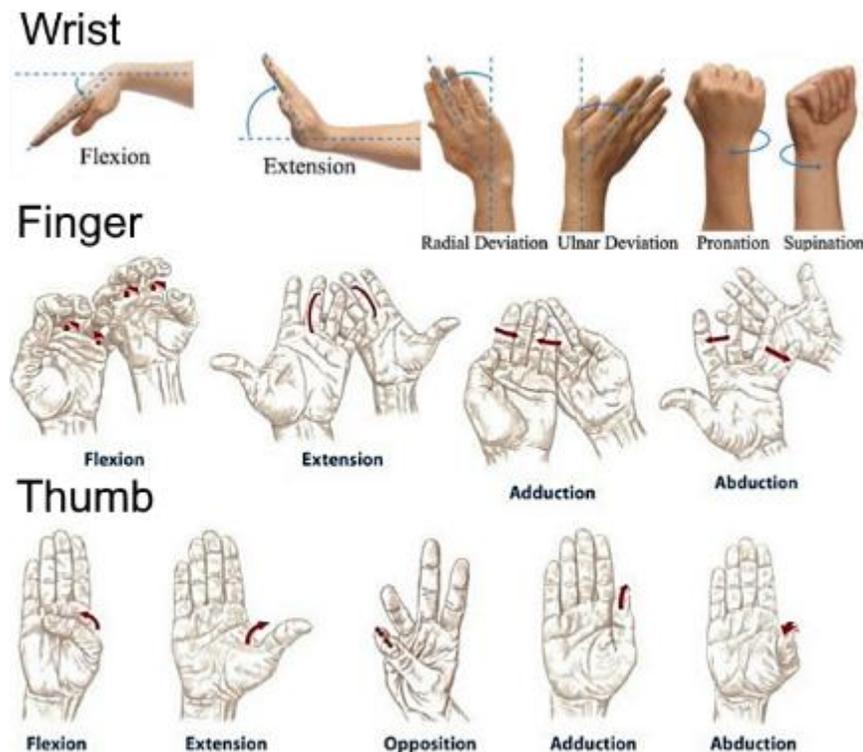


Figure 9: Wrist, Finger, and Thumb Articulation

²⁵ Marchessault, McKay, & Hammert, 2011

²⁶ Ibid

2.3 Transradial Protheses

There are many transradial prostheses available all of which differ in design in terms of their control system types, components, mechanical functions, materials, and manufacturing processes. This section discusses the advantages and disadvantages of each.

2.3.1 Current Issues

There are currently many different prosthetics offered to patients. All have different functions or aspects to them making them unique or better than other products. However, the amount of people who have suffered from traumatic experiences are not looking for extremely complicated prosthetics. Patients desire a chance to return to normalcy and have some assistance in doing so. When they seek out a prosthetic and see one that can handle more weight than an average person would have to lift there would be no need or want in getting that prosthetic. Products are not designing around the needs of the patients and are only adding features they feel would attract the buyers. The prosthetic design took into consideration who would be wearing the device and what they would most likely be doing in the day. The average person would only need to lift around 10lb of weight and need a handful of gestures to complete all the activities of daily living. The designed prosthesis is simple to keep costs low however, was designed while considering how everyday people would use it.

2.3.2 Types

There are two transradial prosthetic designs that are based upon the type of control system. A control system “manages, commands, directs or regulates the behavior of other devices or systems”. Prostheses utilize both mechanical and electrical controls. Some simple transradial prostheses, such as hooks, use purely mechanical systems. The more technologically advanced systems use a combination of both but rely mainly on electrical.

Mechanical inputs refer to a physical movement made by the user that directly powers the prosthetic. Transradial prostheses use the mechanical function of a joint, typically the wrist or elbow. The articulation of the joint in conjunction with a mechanical system, such as pulleys and cables, opens and closes the fingers. Purely mechanical systems are simplistic and provide high sensory feedback; however, they require gross limb movement for operation. Users must have the required limb strength and range of motion necessary to effectively operate the prosthetic. For the purposes of this project, mechanical inputs will only be used to supplement electrical inputs.

Most electrical inputs still require a physical movement made by the user. However, after the initial movement the input is measured electrically and becomes an electrical signal. Typical electrical input methods include pushing a button with a preset function or reading changes in myoelectric impulses created by muscle tissues. Myoelectric refers to the electrical properties of muscles. When a person thinks about flexing a



Figure 10: MyoWare Muscle Sensor

muscle, the brain sends an electrical signal to the muscle. The muscle starts recruiting motor units, or bundles of muscle fibers that generate the force behind the muscles. The harder a muscle is flexed, the more motor units are recruited to generate greater muscle force. The greater the number of motor units, the more electrical activity the muscle produces. Sensors can be used to measure this electrical activity and its changes during flexion and extension. The voltage differential between flexion and extension can be measured and translated into digital signals. These signals can be used as an input. For example, when the bicep is flexed, the voltage will increase and the signal can trigger the prosthetic hand to close. Then when the bicep is extended, the voltage will decrease and the signal can trigger the prosthetic hand to open.

The process of collecting myoelectric input ranges from very complex, sophisticated systems that can accurately determine the user's exact intention for muscle movement. However, much simpler options are available for systems that only require the detection of any sort of muscle flex. These systems, such as the MyoWare Muscle Sensor, use a signal amplifier and electrodes to output a raw signal which can then be read by a microcontroller.

2.3.3 Components

Transradial prosthetic devices use multiple components working together in order to function. The components mimic their corresponding human body parts as closely as possible in structure. The major components are the hand, forearm, and socket.

The hand has three distinct parts: the palm, fingers, and thumb. The palm is important for structural integrity, housing smaller components, and supporting the fingers. It is often used to house electronics and other components that are used to articulate the fingers. The structure must be sturdy and durable so that it can support the fingers and loads of gripping different objects. Prosthetic fingers are often made with two or three joints. The use of two joints strays from mimicking the human hand. In comparison, the DIP at the tip of the finger is eliminated and held stationary. Using two joints, allows for the fingers to support heavier load while three joints, allow for greater dexterity. Mimicking the human thumb is one of the biggest challenges as it has a saddle joint and nine muscles working together to move it. Imitation of this movement is limited by the amount of space available to the designer and the complexity, expense, and quality of the components and electronics necessary. Most prosthetic thumbs only move with two degrees of freedom along two perpendicular planes.

The socket attaches the rest of the prosthesis to the residual limb, providing support and stability. Its design must balance form and function. The form must fit and adjust to the residual limb with minimal slippage. If it doesn't, the amputee can experience pain, sores, blisters, and severe health concerns can arise. The prosthesis will also feel heavy and cumbersome, compromising mobility.

2.3.4 Functionality

Transradial prosthetic devices have multiple functions that work together to mimic their corresponding human body parts as closely as possible in function. The most important function a prosthesis seeks to restore is traditional hand functionality, specifically the ability to grip various objects. Ideally, the prosthesis should also function such that the hand can be articulated and

rotated without excessive use of the shoulder, as a human forearm can rotate independently of the upper arm. A successful transradial prosthesis is relatively aesthetically pleasing, and allows the user to operate normally, without excessive compensation to accommodate the device.

2.3.4.1 Hand Grips

A major and critical function of a prosthetic hand is to grip assorted objects. A person uses many different types of hand grips depending upon the size, shape, and weight of the object, as well as the task that is to be completed. Types of grasps fall into two categories: power and precision grips.²⁷ Designing for the ability to achieve these grips is near-essential to the development of a prosthetic hand device.

Power grips utilize a significant amount of force. The fingers flex around an object in one direction, while the thumb flexes around in the opposite direction. This provides a counterforce to keep the object in contact the palm and/or fingers. Power grips include cylindrical, spherical, and hook grips, as well as lateral prehension if the thumb is adducted away from the fingers.

When a cylindrical grip is used all fingers are flexed around the object, which is usually at a right angle to the forearm. The thumb is wrapped around the object, often overlapping the fingers. When using a spherical grip, all of the fingers and the thumb are adducted around an object, and unlike the cylindrical grip, the fingers are more spread apart. The palm of the hand is often not involved. The hook grip involves the four fingers flexed around an object in a hook-like manner. The MCP joints are extended, and the PIP and DIP joints are in some degree of flexion. The thumb is usually not involved. Figure 11 offers visuals of these grips.

Precision grips require more delicate movement and positioning of the fingers. They tend to hold the object between the tips of the fingers and the thumb. Precision grips involve the intrinsic and extrinsic muscles, the thumb is abducted, and the palm and proximal joints don't move. They are used for fine movement and accuracy; for example, when objects are small or fragile. There are four types of precision grips: pad to pad, also called pinch or palmar; tip to tip, also called pincer; lateral prehension; and lumbrical.

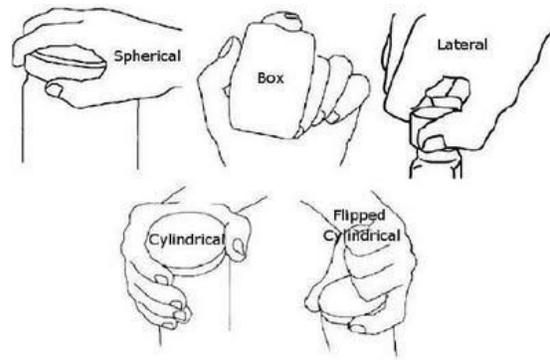


Figure 11: Power Grips²⁸

²⁷ Steinfeld, 1986

²⁸ Behrens, n.d.

When using a pinch grip, the MCP and PIP of the fingers are flexed, the thumb is abducted, and the distal joints of both are extended to bring the pad of the fingers and thumb together. Lateral prehension is the pad of the extended thumb pressing an object against the radial side of the index finger. This type of grip is often used to hold keys, paper, or thin objects. The lumbrical grip, sometimes referred to as the plate grip, flexes the MCP and PIP joints, extends the DIP joint, and the thumb opposes the fingers, holding the object horizontal. Again, visual representations of precision grips can be found in Figure 12 below.

Table 2, adapted from Mathiowetz, V., et al. (1985), shows the average strengths of grasps for males and females in four categories: Grip Strength, Tip Pinch, Key Pinch, and Palmar Pinch. These values are averaged from participants aged 20 to 75+ and across both hands.

Table 2: Average Grip Strengths

	Average Strength (lb.)	
	Male	Female
Grip Strength	98	58
Tip Pinch	16.5	11
Key Pinch	24	16
Palmar Pinch	23	16

Prosthetics try to closely mimic these grips. However, the ligaments that incorporate the joints of the wrist and thumb are numerous. It is extremely challenging to reproduce the same degrees of freedom (DOF). Prosthetics often have fewer degrees of freedom and restricted

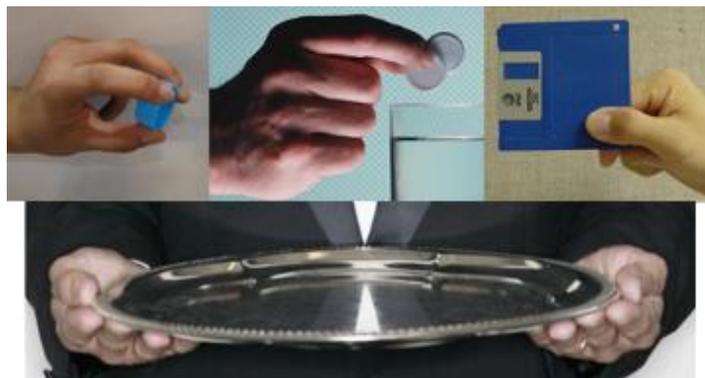


Figure 12: Precision Grips²⁹

movement. Therefore, most prosthetics cannot accomplish all of the grips the human hand is capable of achieving.

2.3.4.2 Fingers and Their Articulation

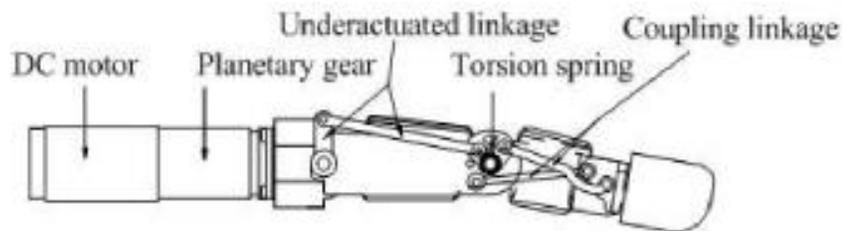


Figure 13: Underactuated linkage design (Multi-DOF Anthropomorphic Prosthetic Hand)

The method by which the fingers of a prosthetic are articulated is an important system as it can have effects on the cost, longevity, and durability of any given prosthetic. Prosthetics typically utilize one of two methods to articulate the fingers: a mechanical linkage system or a pulley system.

Both systems can be implemented to be underactuated, meaning the total degrees of freedom of the system can be greater than the amount of control inputs. The figure below shows how the same linkage can adapt to different surfaces. The effect here was described well in a report from the Harbin Institute of Technology's Robotics Research Institute: "Before contact, the finger behaves as a single rigid body in rotation round the pivot in base joint. When the proximal phalanx [the segment of the finger closest to the palm] makes contact with the object, the proximal phalanx stops, and the other two phalanxes begin rotating and closing on the object because of the effect of the underactuated linkages mechanism."

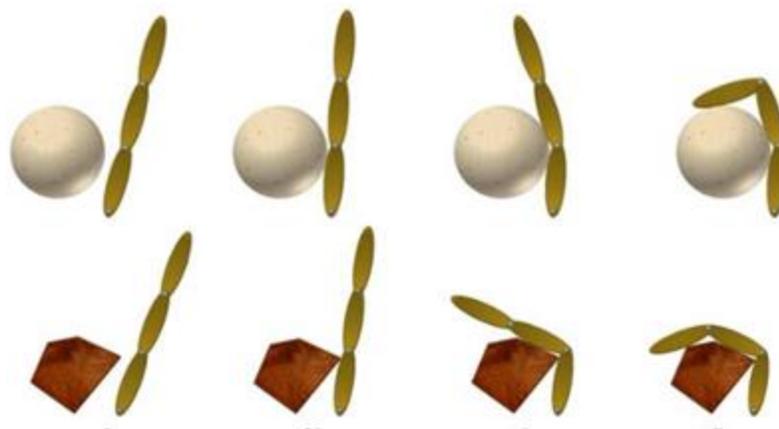


Figure 14: Underactuated Linkage around Spherical and Irregular Objects³⁰

The challenge that arises from using a mechanical linkage design within a finger is the space limitation, and from a budget standpoint, the ability to 3D print the linkage system and

³⁰ Pierluigi, 2011

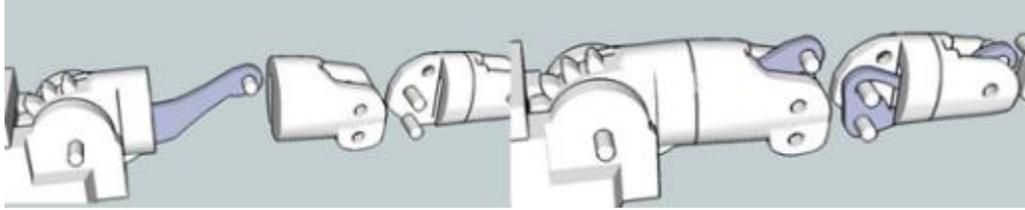


Figure 15: Mechanical Linkage Design

maintain functionality. A linkage design from the Harbin Institute manages the space limitation very well with their finger design. The finger is driven by a DC motor with a planetary gearbox for added torque and is based on four-bar linkage mechanisms meaning it is underactuated.

A finger design posted to Thingiverse had a simple mechanical linkage system with no underactuated linkage meaning the finger overall has only one degree of freedom. The design is an example of a mechanical linkage that is relatively functional and 3D printable.

Another popular method that is most common in budget prosthetics for finger actuation is a pulley system. The concept uses cables internally threaded along separate tracks in the length of each finger. The cable or thread can then be pulled to actuate the fingers by means of mechanical or motor input. The pulley system was used in the 2016 Worcester Polytechnic Institute (WPI) Major Qualifying Project (MQP) titled Design and Manufacture of a Scalable Prosthetic Hand through the Utilization of Additive manufacturing as seen in Figure 16 below. In addition to this MQP, other previous designs include more than one cable, inflexible cable, or electrical actuation.

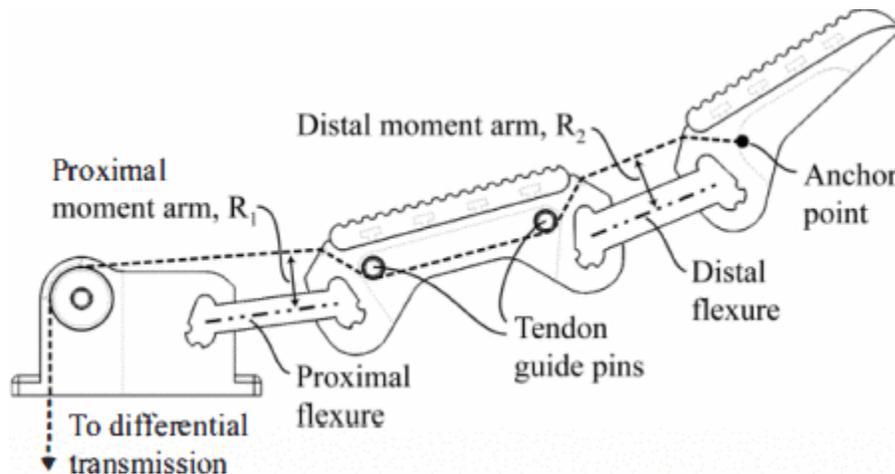


Figure 16: Flexible Finger Joints³¹

2.3.5 Materials and Manufacturing Processes

Prosthetics are made from a variety of materials. Some materials that are commonly used for prosthetics are: carbon fiber, carbon plastic with a low melting temperature so the plastic can be heated and free-formed, or bent, to better fit the user, steel, aluminum, polylactic acid (PLA), Acrylonitrile Butadiene Styrene plastic (ABS), and other plastics such as polyethylene.

The material is very dependent upon the manufacturing process as all materials are not able to be manufactured the same way. One type of manufacturing is rapid prototyping, a subset of additive manufacturing. Rapid prototyping is a group of techniques used to quickly fabricate a model of a part or assembly using 3D computer aided design (CAD) data. This concept fabricates prototypes in a fraction of the time and cost when compared to traditional methods. There are many rapid prototyping technologies. One of these technologies is 3D printing. The advantages of 3D printing are that complexity can be added at no cost, no tooling is required, waste is reduced, less operator skill is required, and some assemblies can be printed already put together. These advantages allow for design alternatives to be printed and tested relatively quickly and at low cost. Innovative, creative design concepts can be modeled and printed to test if the concept works. If it does not work, the amount of time and resources lost are comparatively small to other design processes.

3D printing also has some disadvantages. It has a limited and relatively expensive selection of materials, is difficult to scale, results in parts with reduced mechanical properties, and requires post processing. The printed parts must either be printed with a flat surface or with additional raft or support material. The additional material takes time to remove and is wasteful.

3D printers are available for both personal and professional use. The cost of 3D printers depends on their resolution and material usage, and can range from approximately \$100 to millions of dollars. The 3D printers used for this project to fabricate our designs were a XYZ Da Vinci 1.0, Dimension SST 1200es, Makerbot Replicator 2, and Sindoh 3D printer. The components were printed with PLA of a diameter of 1.77 mm. The printer used is a single extruder and heats to 230 degrees Celsius that prints layers of .2mm. The components are all printed with a 7% to 8% hexagonal infill on a non-heated glass bed.

The two most common materials for 3D printing are ABS and PLA. ABS, or Acrylonitrile-Butadiene-Styrene, is a plastic commonly used in 3D Printing. It is commonly used because of its melting point temperature which coincides with safe heating practices in 3D Printers, as well as its strong mechanical properties. It is also a relatively inexpensive and widely produced material so it is beneficial for consumers to utilize it. PLA, or Polylactic Acid, is a thermoplastic typically made from corn starch. Due to being made from natural materials, it is biodegradable. PLA is also mechanically stronger than ABS so it is a viable candidate for 3D Printing. Similar to ABS, it also has a melting point consistent with the temperature ranges of most commercial and industrial 3D printers.

PLA was chosen as the material of choice for this project for two reasons. First, the fact that it is stronger than ABS gives it an advantage for the project's purposes. Second, is that it is biodegradable. Wanting to sidestep the reality of leaving an environmental footprint with this project, the team decided to pursue PLA as their material of choice.

2.4 Current Technology

There are currently many transradial prostheses commercially available and even more under development. A few relatively inexpensive and innovative designs were evaluated and analyzed for their strengths and weaknesses. These strengths directly influenced the prototype design while the weaknesses were mitigated or eliminated.

2.4.1 Open Bionics' Ada Hand

The Ada Hand is a robotic hand designed by Open Bionics. It is 5 degree-of-freedom, fully articulated hand actuated by five Firgelli linear actuators and braided thread. All of the actuators are housed in the palm of the hand. Open Bionics describes it as "...perfect for anyone that is doing a project with robotic hands or wants a neat, light, and functional robotic hand for use with a humanoid robot. It's an excellent platform for research into prosthetics, object grasping and many human-robot-interaction applications".³³ Therefore, despite its human characteristics, it is not recommended or intended as a prosthesis. However, due to its articulate nature, it can be used as inspiration for designs. Its very anthropomorphic aesthetic and its ability to achieve numerous gestures are incredibly ideal for prosthetic hands.



Figure 17: The Ada Hand³²

2.4.2 e-NABLE's Limbitless Arm

e-NABLE is an organization dedicated "...to [creating] free 3D printed hands for children all over the world who have been born missing fingers or who have lost them due to accident, illness or war".³⁵ The organization has produced over 2000 designs for those in need of a prosthetic arm. Most of the designs are mechanically powered by a functional wrist or elbow. The Limbitless Arm is e-NABLE's first myoelectric design. "This experimental design was created for individuals with above elbow limb differences by a team of students at University of Central Florida".³⁶ The arm is an open-source design featuring an Arduino Micro microcontroller, a single servo capable of producing torque around 12.1 kg-cm, muscle sensors, and Kevlar survival cord to move the fingers. A disadvantage is that since only one servo is used, the hand can only open and close. However, the Limbitless Arm acts as a decent baseline.



Figure 18: Limbitless Arm³⁴

³² Ada Hand Kit, n.d.

³³ Ibid

³⁴ The Limbitless Arm, n.d.

³⁵ Ibid

³⁶ Ibid

2.4.3 InMoov

InMoov is an “...open source, 3D printed, life size [humanoid] robot”.³⁸ The arm features five servos with a servo controlling each finger. The servos are controlled with an Arduino microcontroller. Several videos of the arm have been posted showing the hand switching between a wide array of gestures, such as those for rock-paper-scissors, the “rock on” hand symbol, the peace symbol, pointing, and a “count down” by closing fingers individually.³⁹ InMoov was designed for a specific robot and is not a prosthesis. However, it is very usable as inspiration for designing a hand capable of numerous ADLs and gestures.



Figure 19: InMoov Hands³⁷

2.4.4 Rehabilitative Robotic Glove

Although it is not a replacement for missing arms or hands, the Rehabilitative Robotic Glove does act as an example of durable string-based actuation. The Rehabilitative Robotic Glove is a medical device designed by a WPI MQP meant to aid the rehabilitation of those who had recently undergone a stroke. “This glove utilizes a cable system to open and close a patient’s hand. The cables are actuated by servomotors...”⁴¹ The system uses Kevlar k49 cables due to their tensile strength and low elasticity. Cables are placed on each side of each finger and attached to a respective servo and spool. This, as a result, always pulls the fingers to a desired position based on which direction the servos move. This type of system could replace elastic thread used in traditional prosthetic designs. The benefit of this is the lack of elongation of the thread that can effectively render the hand useless after a period of time. However, more cables would need to be routed throughout the hand and proper sizing of the spools would be required.



Figure 20: Rehabilitative Robotic Glove⁴⁰

³⁷ DivideWorks, n.d.

³⁸ Ibid

³⁹ Ibid

⁴⁰ Delph et al., 2012

⁴¹ Ibid

2.4.5 Multi-DOF Anthropomorphic Prosthetic Hand

The Multi-Degrees-of-Freedom Anthropomorphic Prosthetic Hand developed at the Harbin Institute of Technology's Robotics Research Institute has some of the most sophisticated hardware and software considering its size and anthropomorphic design. The thumb, the index finger, and the other three fingers are each actuated by a DC motor respectively that are all contained within the palm. The fingers operate on an underactuated mechanism that allows for a wide variety of self-adapting grips, and an opposable thumb actuates on a spherical bearing allowing for a force and pinch grips.

The hand enclosure is made of aluminum, and the components comprising the mechanical linkages have been fabricated out of steel. This means a redesign of the linkage would be necessary for an additive manufacturing process. However, what separates this hand from other designs are the sensors it utilizes to implement a control system for the position of each finger. A torque, position, and force sensor is included in each finger and a low-power microcontroller uses the input from these sensors to drive the motors. By implementing a control system like this, it is not necessary to pre-program grips as the fingers will automatically adjust to the object being grasped.⁴²

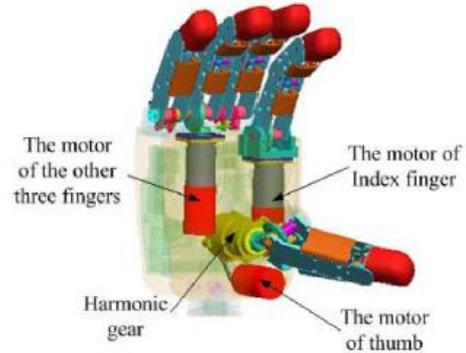


Figure 21: Three motor design for anthropomorphic hand

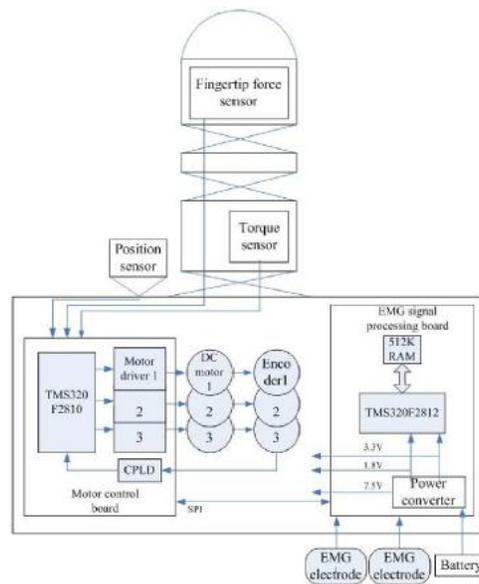


Figure 22: Control System for Force Feedback Controlled Finger

2.4.6 Design of a Human Hand Prosthesis

This Major Qualifying Project from WPI in 2012 gives additional insight into the implementation of a mechanical linkage design in a prosthetic. The “...design incorporates five individually actuated fingers in addition to powered thumb roll articulation...” and also has a simple feedback control system in the form of a force sensor and light emitting diode (LED) built right onto the forefinger. The actuation system for the four fingers is very limited consisting of a single bar connecting the knuckle joint to the distal phalynx. The linkage could be easily converted to a 3D printable design and then modified for additional degrees of freedom.

The mechanical linkage for the thumb attempted to maintain the two degrees-of-freedom of a human hand by using a two motor system for pitch and roll respectively. The motors controlling both axis can be controlled independently adding three additional grip capabilities. Each finger including the thumb has a potentiometer mounted to each rotational axis which gives the microcontroller an idea of phalange positioning for further motor control.⁴³

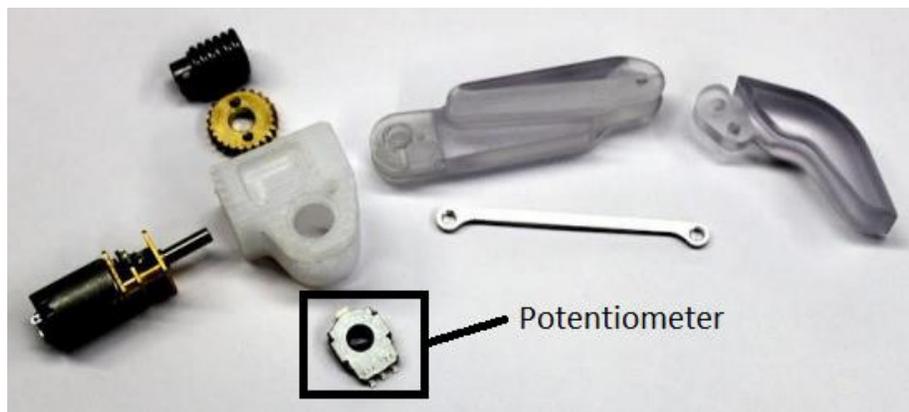


Figure 24: Finger Actuation System

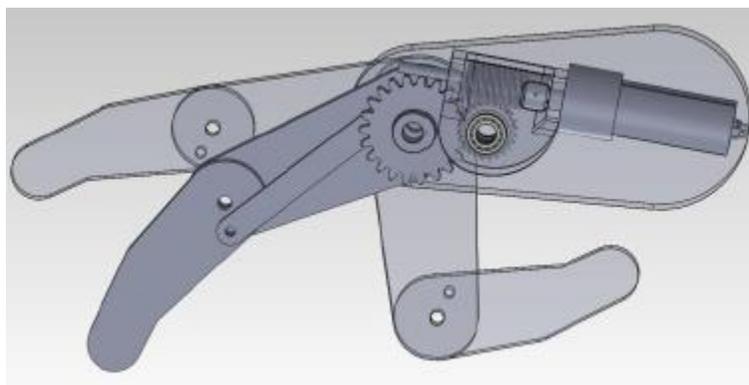


Figure 23: Mechanical Linkage for Finger Actuation

⁴³ Ventimiglia, 2012

2.4.7 Socket

Socket design is crucial to the success of the overall prosthesis. Well thought out socket designs and careful consideration of residual limb preservation set the stage for patient success--maximizing range of motion, providing stability throughout daily activities, and comfortably distributing the forces exerted on the residual limb during movement and suspension. In contrast, poor socket design will often drive a person to abandon the prosthesis.⁴⁴ The challenge of achieving the best socket fit is that the residual limb changes shape and size overtime.⁴⁵ Multiple design approaches have evolved to achieve this. There are five standard design approaches: vacuum suspension, bladder-controlled, compression/release stabilized (CRS), 3D printed, and mechanically adjusted sockets.

2.4.7.1 Current Socket Technology

Sockets that don't fit and are uncomfortable lead to critical health problems. The health problems can be severe enough that the added benefits the functions provide are outweighed by the additional health problems. When this happens, the prosthesis is useless and unused. Sockets that don't fit can cause skin, vascular, and lymphatic problems, tissue damage, nerve damage, pain, and discomfort. All types of prosthetic sockets can cause skin problems. Unfortunately, these problems are often dismissed, forgotten, or ignored.

The cause of these skin problems is twofold. First, these problems are caused by increased normal, shear, and frictional forces on the residual limb. Secondly, they are caused by layers of socks or gel sleeves surrounding the residual limb.⁴⁶ The socks are a necessary component of many types of prosthetic sockets in order to achieve a tight fit. It is common to wear layers of thick socks to compensate for daily changes in the size and volume of the limb. Unfortunately, the socks and the socket itself insulate the residual limb, building up heat. This residual heat causes sweat on the skin. The sweat compounded by a lack of airflow leads to a multitude of skin problems.⁴⁷ Additionally, sweat contributes to prosthetic odor, which was identified as a problem in the survey of amputees.⁴⁸ These skin problems include but are not limited to: ingrown hair, rashes, skin irritation, odor, erythema, blisters, ulcers, and skin thickening.

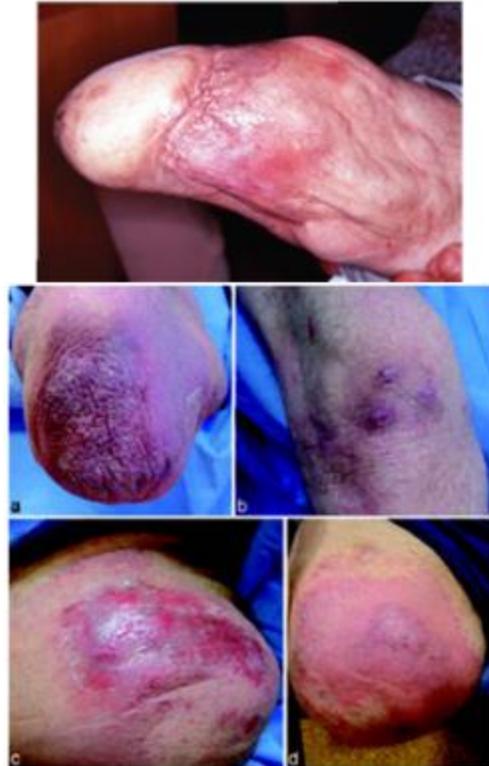


Figure 25: Photos of residual limbs suffering from skin problems

⁴⁴ Lake, 2008

⁴⁵ Ibid

⁴⁶ Maguire & Boldt, 2013

⁴⁷ Mak, Zhang, & Boone, 2001

⁴⁸ Legro et al., 1999

The vascular response of the residual limb is also important because ischemic injury, the restriction of blood flow to the limb, can cause pressure sores and localized malnutrition. Epidermal forces, forces against the skin, are a major factor associated with vascular problems. More explicitly, decreased blood flow occurs with increased application of either normal or shear forces. In addition, the prosthetic device affects the lymphatic system. Lymphatic function is associated with skin health in the form of tissue edema.⁴⁹ Accumulation of lymphatic waste could occur if external forces hindered the flow of lymph fluids, a situation which could occur from the forces applied to the limb in a socket.

The fit of the socket can address these issues. The fit of a prosthetic socket is the most important feature as identified by amputees in a survey when compared to other factors such as weight or ease of use of the prosthesis. The fit of the socket is the key to maximizing range of motion, providing stability throughout daily activities, and comfortably distributing the forces exerted on the residual limb. The challenge of achieving the best socket fit is that the residual limb changes shape and size overtime.⁵⁰ Over the course of months, the residual limb can drastically change in volume with the loss of muscle mass. Over the course of hours and days, the residual limb has smaller volume changes.

One research team, concerned about the effects of slippage, due to improperly fitted sockets, in sockets causing unnecessary frictional force, measured the amount of slippage that could occur for sockets to retain a good fit. Well-fitting sockets had slippage of 2mm to 6mm.⁵¹ In this study, researchers concluded slippage substantially greater than 6mm causes user distrust of the prosthetic limb and severe friction on the limb causing the aforementioned frictional skin problems. Slippage less than 6mm puts extra pressure on the limb causing issues such as pressure sores and ulcers. Intensity and duration of load application of the residual limb are inversely related to ulcer production. Additionally, this increases limb temperature, contributing to sweat production in the socket.⁵² Many types of skin problems such as these can deter amputees from using the device as even mild skin problems cause discomfort and can lead to infection or ulcers if not treated correctly. It is estimated that 75% of amputees will experience skin issues, causing possible decrease in socket use.⁵³

The way the socket manages and adjusts to these changes in limb size and volume directly impacts the fit and comfort of the socket. There are multiple methods that sockets adjust to these changes. The most common methods are: vacuum suspension, bladder-controlled, compression/release stabilized, exact limb replica, and mechanically adjusted sockets.

2.4.7.2 Vacuum Suspension Sockets

Vacuum suspension is a socket method for managing residual limb volume. The user wears a liner or prosthetic sock that forms an airtight seal inside the socket, as shown in Figure 26. Skin suction is a type of vacuum suspension that incorporates a one-way valve to create a seal between the limb and the socket. This seal exerts a positive pressure when inactive and a

⁴⁹ Mak, Zhang, & Boone, 2001

⁵⁰ Lake, 2008

⁵¹ Commean, Smith, & Vannier, 1997

⁵² Mak, Zhang, & Boone, 2001

⁵³ Highsmith & Highsmith, 2007

negative pressure when active. Other forms of vacuum suspension use a pump to remove air from between the limb and the socket which applies a constant negative pressure to the limb.⁵⁴ Vacuum suspension has the added benefit of managing residual limb volume and can increase total limb volume to better keep the skin in contact with the liner and socket.⁵⁵ The technology also maintains a better socket fit than standard prosthetic sockets, reducing discomfort or pain from wearing the prosthesis throughout the day. However, these types of sockets need to initially be fitted to the individual for effectiveness. Also, for larger volume changes, the addition of socks or small air bladders in the socket is required. Furthermore, they can cause skin issues due to sweat accumulation or an allergic reaction to the socket material. This is because the gel liners used can cause ingrown hairs or rashes.

2.4.7.3 Bladder-Controlled Socket

Bladder-controlled sockets adjust their fit by increasing the pressure of one or more bladders on the inside of the socket. The bladders apply pressure to the residual limb to hold it in place. The bladders accomplish this with either pneumatic or hydraulic systems that inflate their bladders with a fluid. Most bladders are manually pumped up or deflated with ambient air to their desired comfort and pressure level. An advantage to bladders is that they can be added to an existing socket and filled with air or liquid in order to replace volume lost by the residual limb, as shown in Figure 26.⁵⁸ The Smart Variable Geometry (SVG) socket uses liquid-filled bladders powered from the cyclic motion of walking.⁵⁹ The liquid-filled bladders replace volume lost by the user's residual limb and apply pressure to the limb to keep the user's limb in place. The device's maximum pressure can be adjusted by a prosthetist who also decides on the number and placement of bladders. The device's main advantage is that it does not rely on electrical power to pump up the bladders. However, this means that the user must be in motion in order to pressurize the bladders. Small motions can potentially cause a loose fit and irritation of the residual limb. The SVG design also does not allow for the bladders to be individually controlled. Individual control of the bladders could allow for more precise control of volume loss in the socket and increased comfort for the user. A disadvantage is that higher pressure can have negative effects on the user's limb, potentially cutting off blood flow and causing tissue damage.⁶⁰ The controls and fluid are also bulky and heavy.

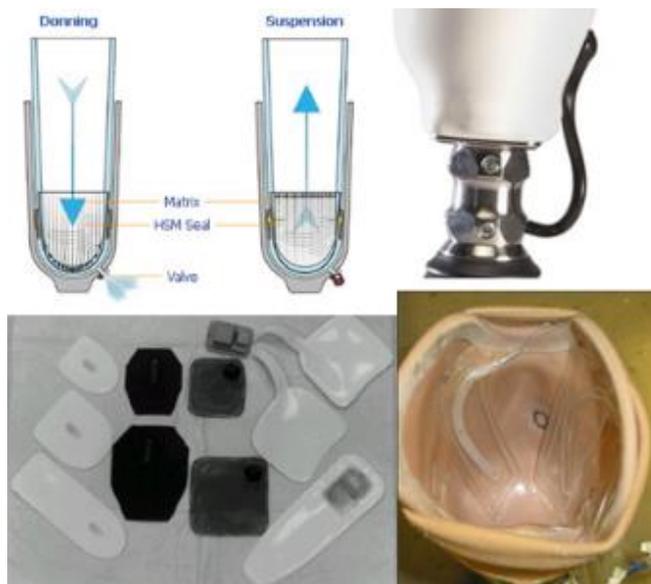


Figure 26: Vacuum suspension sockets⁵⁶ and Inflatable bladders⁵⁷

⁵⁴ Beil, Street, & Convey, 2002

⁵⁵ Street, 2007

⁵⁶ Hedef, n.d.

⁵⁷ Sanders, 2001

⁵⁸ Sanders & Cassisi, 2001

⁵⁹ Greenwald, 2003

⁶⁰ Sanders, 2001

2.4.7.4 Compression/Release Stabilized Socket

The Compression/Release Stabilized (CRS) socket uses pre-compression to save amputees' energy. Conventional prosthetic sockets only compress the residual limb during movement. When an amputee with a conventional prosthetic socket wants to move their limb, they must first compress the soft tissue between the bone and the socket before any movement occurs. This compression is done subconsciously as part of regular movement with a conventional prosthetic socket. This extra movement wastes the time and energy of the wearer. Due to the pre-compression of the CRS socket, all energy output directly moves the limb. This leads to increased energy output efficiency, range of motion of the end effector of the limb, and user control of his or her limb.⁶²



Figure 27: Compression/Release Stabilized Sockets⁶¹

The CRS socket raises safety concerns such as blood flow restriction. While the total area of compression is reduced, there is higher compression placed on the remaining areas of the limb. This high compression could cause further issues for those with blood circulation problems, such as those with heart disease or diabetes. Another concern is discoloration of the limb, which can indicate soft tissue damage. Once the CRS socket is removed after wearing for 3-4 hours, it can take another 3-4 hours for the reduction of redness in the residual limb. This discoloration also brings up concerns about long term use and if the device would cause a deformation of the limb.⁶³ While there are currently no user reviews about the CRS socket because the device is still in clinical testing, an overall review of prosthetic users who used restrictive sockets similar to the CRS socket was analyzed. Users reported that for the first 2-3 years, they felt discomfort at the areas of restriction.⁶⁴

⁶¹ Bio Designs, n.d.

⁶² Alley et al., 2011

⁶³ Ibid

⁶⁴ Legro et al., 1999

2.4.7.5 Exact Limb Replica

The importance of a socket's fit led to exact limb replicas. Initially molds and casts were made of the limb to create sockets that fit snugly. Now, advances in scanning technology and 3D printing, have led to multiple amateur prosthetic and socket designs. Every residual limb is different and custom sockets must often be individually fabricated. 3D printing simplifies the process of custom sockets. The key elements of this process are the measured data and the recorded residual limb topology. It is essential for this data to be both precise and accurate for the socket to fit correctly. The advantages of this process is that the prosthetic socket is an exact fit for the amputee's residual limb. Unfortunately, the process often requires several prints and fittings before a sufficient level of comfort is achieved.⁶⁶ The socket also doesn't account for volume fluctuations in limb size. The amputee still has to wear multiple socks in order to adjust for any day-to-day fluctuations, causing heat retention, chaffing, and rashes.



Figure 28: 3D Printed Socket Creation Process⁶⁵

2.4.7.6 Mechanically Adjusted Socket

Mechanically adjusted sockets are often static systems with multiple manual controls that make micro-adjustments. These controls allow the user to make small adjustments throughout the day to accommodate change in limb volume. Larger changes can also be made as the limb changes over the course of months or years. Revolimb, shown in Figure 29, powered by Click Medical's Boa Closure System and Martin Bionic's Socket-less Socket, also shown in Figure 29, are examples of mechanically adjusted sockets. These sockets allow the user to easily and quickly adjust the fit of their socket to their current needs. The user can adjust for a tighter fit for more performance, or reduced compression for resting and sitting. The Revolimb system utilizes a series of panels along the outside of the socket that add or reduce compression to the limb with the turn of a dial.⁶⁷ The Socket-less Socket utilizes all adjustable carbon struts as a framework with flexible cross connectors and dynamic straps so that the entire socket is adjustable. For daily adjustments, the straps easily ratchet to adjust compression. For long term limb changes, the

⁶⁵ Devadass et al., n.d.

⁶⁶ Ibid

⁶⁷ Click Medical, n.d.

carbon struts and cross connectors fastened by rivets can change the overall shape and size of the prosthetic socket.⁶⁸



Figure 29: The Revolimb⁶⁹ and the Socket-less Socket⁷⁰

2.5 Impacts and Ramifications

2.5.1 Manufacturing, Sustainability and Environmental Aspects

To manufacture the prosthesis the current process would take time. Each prosthesis would have to be hand assembled and all the parts would have to be gathered separately. The current process for creating the hand is to use 3D printed technology. The amount of time it would take to print every piece in mass quantity would not be worth the time and effort. However, once a patient has a prosthesis it should last for an extended period (at least 6 months). There may be a need to have replacement parts if something were to break and having the parts 3D printed is advantageous. The model could be sent to a 3D printer close to the patient and they could even pick it up the same day if the printer is not being used. If the patient has their own 3D printer then they could print a new part and immediately have it. Since most of the parts of the prosthesis are 3D printed they could keep using it as long as the electronics work. Should the electronics fail, after ordering new parts they should be able to get them within 3-5 days and continue to use the prosthesis.

The material that the prosthesis was printed with is Polylactic Acid or PLA. It is a biodegradable substance that usually takes 30 days to be completely dissolved. Compared to other devices on the market that use other materials like plastics or metals when the device is discarded it is not recycled. Other devices cannot be broken down and have to be thrown away when they are finished being used or break.

⁶⁸ Martin Bionics, n.d.

⁶⁹ Click Medical, n.d.

⁷⁰ Martin Bionics, n.d.

⁷¹ Baily, n.d.

The components cost 375\$ to obtain. With the addition of using a service to print the components it could roughly cost 450-500\$. For prosthetics with the functionality of the one designed it would cost hundreds if not thousands of more dollars to achieve the same functions.⁷¹ Using 3D components makes it less expensive and easier to manufacture than other models on the market.

2.5.2 Ethical Concern and Health and Safety Issues

The highest design specification of the prosthesis was that it would be safe to use over long periods. The biggest area of concern would have been between the socket and the patient as that is where the prosthesis attaches. The skin could grow irritated over time if the wrong material was used for padding. From testing, it showed that there was minimal slippage and irritation on the skin after the contact points of the socket was worn. Other aspects of the prosthesis should not cause any harm to the patient while they are using it. The prosthesis was designed to help those in need and provide them with a way to try to return to normalcy.

Since there are many people suffering from the loss of a limb it is difficult to provide a way to help everyone. Those who served in the military, for example, should they receive a prosthetic for free for helping serve the country? There is a dilemma currently that the products on the market to restore functionality and normalcy are very costly. It is not feasible to provide a free prosthetic to everyone who needs them, but at the same time it is very hard to decide who does receive one. The current design could fill the void that currently exists. Not everyone is able to afford a fully functioning prosthetic and the prosthesis designed could change that. More people would be able to afford it and would not have to make tough decisions of who gets assistance and who does not.

2.5.3 Economics, Political, and Societal Impacts

There are many prosthetics on the market today. The cost could be between a couple hundred dollars to even a thousand dollars. People who have gone through traumatic experiences who have lost a limb may not be looking for one that is able to do everything their old limb could do. They may want to have a prosthesis that can do the basics and help them get by. The less expensive prosthetics could provide the bare minimum needs, but may need constant fixes or may be inconvenient to use. More expensive prosthetics could provide all the functions desired, but is generally too expensive to purchase and maintain over time. Our current 3D printed prosthetic device would allow a much lower cost and offer the same functionality as the more expensive ones.

If the designed prosthesis were to become a commercial product it would most likely change the market of prosthetics. The amount of people that would be able to obtain a prosthetic would increase and if in the future there are more and more people in need it could continue to help everyone, not just the people who can afford an expensive model. Those who might not have the health insurance to cover the cost of a prosthetic would be able to obtain one as well. It would help not just those effected now, but even people in the future who might need assistance later in life.

3. Methodology

Standard methods for engineering design were utilized. The problem was articulated in detail. Design goals were generated, defined, and ranked to describe an idealized design. The terms of a successful solution were defined by the design specifications. The ideation process generated multiple possible designs. These design alternatives were evaluated and ranked against the design goals and specifications using decision matrices. The highest ranking and best solution was selected to move forward. The selected design was modeled and a prototype manufactured. Tests were created based upon the design specifications. The prototype underwent these tests to determine if the design met the design specifications and was successful. The tests results show the strengths and weaknesses of the design, revealing areas for further development.

3.1 Design Goals

The project design goals were identified, defined, compared and contrasted, and ranked. The design goals identified were: safety, ease of use, durability, comfort, range of motion, maximum capable load, serviceability, weight, scalability, cost, ease of assembly, environmental factors, aesthetics, time to assemble, and time to print. The design goals were compared against each other using a weighted decision matrix. If the vertical design goal was more important, the value “1” was recorded. If it was of equal importance, the value “0.5” was recorded. If it was less important, the value “0” was recorded. The total was then tallied. The design goal with the highest value was ranked as number “1” and the least as number “15” and so on. The weighted decision matrix used to determine the ranks can be found in Appendix D.

Ranked Design Goals

1. Safety
2. Ease of Use
3. Durability
4. Comfort
5. Range of Motion
6. Maximum Capable Load
7. Serviceability
8. Weight
9. Scalability
10. Cost
11. Ease of Assembly
12. Environmental Factors
13. Aesthetics
14. Time to Assemble
15. Time to Print

Safety

The safety of the prosthetic is imperative due to the fact that it is meant to assist a patient in their daily lives and not cause them harm. If the device is not safe, then it becomes effectively useless and will not be used. Safety includes many factors such as excessive heat, electrical shocks, reduction of blood flow, ingrown hair, rashes, skin irritation, odor, erythema, blisters, ulcers, and skin thickening

Ease of Use

Ease of use is an incredibly important factor to consider when designing a device. If the user cannot understand how to use or does not have the abilities needed to use the prosthetic, then there would be little reason to use it. The controls must be easy to understand and use simple functions for anyone to be able to use the prosthetic.

Durability

The durability of a prosthetic is crucial. It should be able to withstand the daily loads it is put under with little wear. A device that cannot withstand these loads or fails after a short time and constantly needs repair presents itself as more of a hindrance than an asset. The more durable the prosthesis, the less it would need to be serviced, reducing both the cost of the maintenance and the time the user cannot use their prosthesis.

Comfort

Many different factors are considered for the comfort of the prosthesis. The socket where the user and the prosthesis are joined must be comfortable over long periods of time. The amount of heat retained when wearing the prosthetic must be low so it can be worn over long periods of time. It must cushion the amputation site so it does not irritate the skin and it should be secure without causing stress on the existing arm.

Range of Motion

The prosthetic must complete a wide range of motion to ensure the ability to aid in daily life. It must have the capability to complete a number of gestures to allow a person can continue to live a normal life. If the hand does not have a wide range of motion, then there would be no point in using the prosthetic for daily use.

Maximum Capable Load

The amount of weight that the prosthetic can successfully hold is another important factor. If it cannot support a reasonable amount of weight, such as a gallon of milk (8.6 lb.), it would not be able to complete many of the activities in life. A prosthetic incapable of handling these weights serves only the purpose of aesthetics.

Serviceability

The easier the prosthetic is to service, the more desirable it becomes for potential users. With expected wear-and-tear, if a part breaks or fails over time, but can be fixed within a relatively short amount of time and with little effort, that prosthetic becomes far more desirable to that given user.

Weight

The weight of the prosthetic is important because if it was attached to a patient and it could not be lifted by them, there would be little use to it. The prosthetic must be light enough for people of different builds to be able to use it for extended periods of time without feeling tired or inconvenienced. With the inclusion of many different electrical components, the weight needs to be focused on or the device could easily become too heavy and unusable.

Scalability

There are different kinds of people that need prosthetics and this project aims to cater to them. If there is a need to change the sizing to make a better fit for a patient, it is important to be able to do so to allow more people to benefit from the prosthetic.

Cost

With different components being used in the prosthetic, it must be taken into consideration who will be able to afford the device. The cost must be kept reasonably low while maintaining a high standard of quality so there is the possibility for more people to be able to use the prosthetic.

Ease of Assembly

When a patient obtains the prosthetic, they would need to be able to assemble it themselves with the instructions provided. It should be intuitive and simple to follow the instructions so patients are able to do it themselves. Making a prosthetic that worked, but needs others or a professional to assemble would not be practical or useful to a patient that has no access to either.

Environmental Factors

The hand itself must be able to withstand the constant use throughout different environments. It cannot fail because the patient uses it in the sun or splashes water onto it. The purpose of the prosthetic is to allow the patient to continue in their daily life and having to significantly limit them to avoiding certain conditions.

Aesthetics

A key purpose in having a prosthetic is the desire to return to normalcy. If the hand was aesthetically unpleasing or did not resemble a human hand, it would not be desired by many. It should function well while at the same time being a product that people would willingly to use and show.

Time to Assemble

When considering the patients using the prosthetic, it is necessary to think about how long it will take them to assemble it. If a large amount of time is required to put the prosthetic together, it could frustrate many and deter them from using the product. It should be able to be put together in a relatively short amount of time with as little stress as possible.

Time to Print

The prosthetic should not take an extensive amount of time to print if there was a need to recreate a certain part. 3D printing is not instantaneous. As such, a part or component should be

designed to take as little printing time as possible as to allow for the part to be efficiently replaced or fixed.

3.2 Design Specifications

The prosthetic will be designed to fulfill the following specifications in Table 4. These specifications were determined through by combining the weighted design goals and the design decisions previously discussed.

Table 3: Design Specifications

Specification	Quantitative Value	Qualitative Description
Safety	N/A	Will not harm the user through scratching, cutting, burning, or be able to complete involuntary movement.
Maximum Operating Temperature	140°F (60°C) +/- 10°F (5°C)	At around 140°F, PLA will reach its glass transition temperature
Minimum Operating Temperature	-10°F (-23.3°C) +/- 10°F (5°C)	At around -10°F, most rubbers will begin to reach their glass transition temperature. Significant performance degradation will occur around 0F.
Ease of Use	N/A	Will be easy for users to trigger movement with simple movements. Will not feel awkward or be causing unusual or unnatural movements to trigger function.
Life Expectancy	2000 cycles, with components being replaced when needed.	The base of the prosthetic will be able to last while components that wear will need to be replaced. Additionally, number of times the hand can open and close before reduction in performance will be weighed into this goal.
Socket Fit Comfort	minimum of 5+ on a 1 to 10 scale	Socket comfort score (SCS) based upon numerical rating scale (NRS), 0 being least and 10 the most comfortable score ⁷¹
Range of Motion Wrist	0 to 180 +/- 10 degrees, 1DOF	Angle 0 when resting the palm flat to resting the back of the hand flat
Range of Motion MCP	0 to 90 +/- 5 degrees, 1DOF	Joint and knuckle. Angle 0 at full extension, curving inwards

⁷¹ Hanspal, Fisher, & Nieveen, 2003

Range of Motion PIP	0 to 90 +/- 5 degrees, 1DOF	Joint at end of proximal phalanx
Range of Motion DIP	0 to 90 +/- 5 degrees, 1DOF	Joint at end of intermedial phalanx
Range of Motion TMC	Opposable thumb, 2DOF	Joint at base of thumb
Range of Motion IP	0 to 90 +/- 5 degrees, 1DOF	Joint at distal end of thumb
Maximum Capable Load	5 to 11 lbf (22-49 N) +/- 1 lbf (4.5 N)	Total allowed force on the fingers from carrying a weight
Serviceability	N/A	Universal replacements will be readily available. Information for purchasing components will be provided with the product.
Weight	5 lb. (2.27 kg)	Weight of the entire assembled prosthetic and socket
Scalability	Provide dimensions and sizes for ages of 16 and up.	Based upon average size of fingers and capable grip strength. Equations and relations in the model will be created so more customers can benefit from the product.
Cost	\$1000 +/- \$100	Cost of all printed and non-printed parts, including wires, electronics, hardware, etc.
Difficulty to Assemble	16 year age minimum for assembling the product.	16 years is a common age for safety understanding. At this age, the person will also be able to fully understand written directions that will come with the product.
Environment Factors	Resist water from electrical components	The product will resist water from the electronic.
Aesthetics	6+	Numeric scale of 0-10, 0 being least and 10 being most appealing.
Time to Assemble	6 +/- 1 hours	Cleaning/finishing and assembling parts and electronics with the given tools by someone 16+.
Time to Print	<60 hours	Time for all parts to print.

4. Design

With sufficient research completed on all aspects of a prosthetic, and design goals and specifications established, designs were developed for each component of the proposed prosthetic. The designs include models developed in SolidWorks that are able to be fabricated using additive manufacturing along with a description of all materials necessary to construct the component. Additionally, diagrams and flowcharts are provided to describe the operation of electrical systems of the design. The following sections present the designs for each component of the prosthetic hand. For ease of discussion, the diagrams in Appendix G: Model Prototype Images will be used to denote which portion of the prosthetic is being referred to.

4.1 Hand

The hand must be durable, functional, and have a sense of natural movement to the user. The hand has been designed with three elements: the palm, the thumb, and the fingers. The palm in this project will serve the purpose of guiding the Kevlar thread to its appropriate finger and housing electrical components for finger movement. The thumb is its own element due to its important role in synchronizing with the others fingers for gripping purposes. The main difference will be in its physical design while its movement method and mechanic system will be the same as the fingers. The thumb will serve mainly as support and assistance in gripping objects and supplying the force necessary for interaction with various objects. The fingers play the largest role in the hand and thus will be three-jointed. This adds a sense of reality and functionality for the user and also aids in gripping and interaction with objects. The image below reflects the final model. The final model utilizes 3D printed pins for the joints.

4.1.1 Finger Design

The fingers were the primary focus of the hand as they will have the most interaction between the prosthetic and the objects being handled. The hand must be able to complete all essential ADL's and therefore must have some system for finger actuation. Actuation here refers to the system by which the fingers will be set in motion, enabling them to open and close. Through research the team found multiple methods for achieving such actuation, but only a few

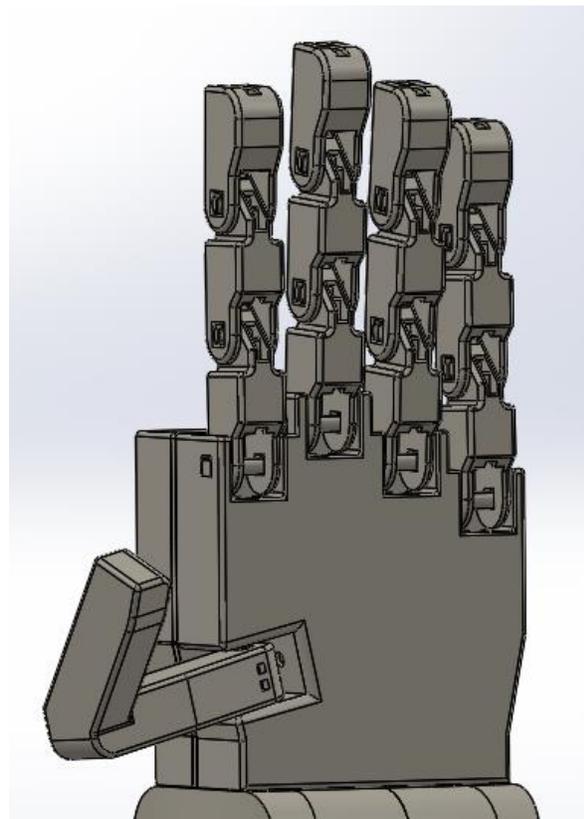


Figure 30: SolidWorks Model of Hand Design

allowed the range of motion necessary for significant ADL completion. The design being pursued involves using Kevlar threads to both pull the finger into its closed position and then back into its open position. This method gives the fingers the ability to adapt to object shape and size and also provide the necessary force required to perform individual, everyday tasks. The actuation of the fingers is explained below.

The fingers each contain channels that have threads through them to actuate the fingers. These pulley channels are referred to as “close” and “open” and run along the bottom and top tracks respectively. Both cables reside on one side of the pin connecting each finger segment. When activated, they provide a moment on the pin causing the segment to move towards the direction of the cable. Activation occurs via servo motors. The thumb, index finger, and middle finger each have a dedicated servo. The remaining two fingers use a single servo motor, resulting in a total of four servos used in this design. Each of these motors will have their standard parallel gear replaced with a two piece track which can be seen below. The only exception to this design is the servo actuating the pinky and ring finger will have a four piece track to actuate two fingers simultaneously.

When the thread is pulled by the servos, the threads in the close channel will torque around the pins that will cause the finger to actuate to its closed positions depicted by Figure 32

The finger’s joints will actuate until the object it is gripping forces it to stop. The other joints will actuate until the finger is completely gripping the object with the necessary force.

Each piece of the track will be dedicated to either the “open” or “close” cable. These cables will be fixed via screw to one tangential location on the track. The process will be identical for each cable; the only difference being that each cable will run in opposite directions. When the servo is activated, for example to close the hand, the “close” cable will begin wrapping around the track until the servo is deactivated. The same process would occur for the “open” cable to open the hand when the servo was activated in the opposite direction. Having both cables is essential to this design as it results in fewer moving parts, removing the need for springs, and the ability to use wear-resistant materials.

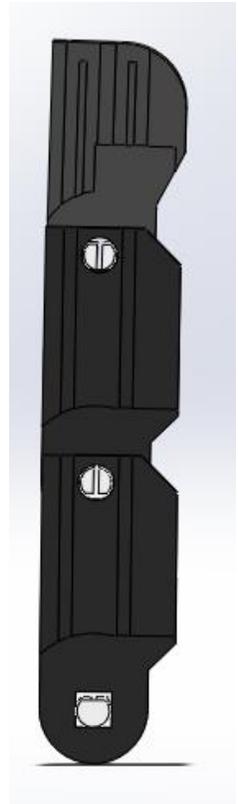


Figure 31: Push Pull Pulley Design

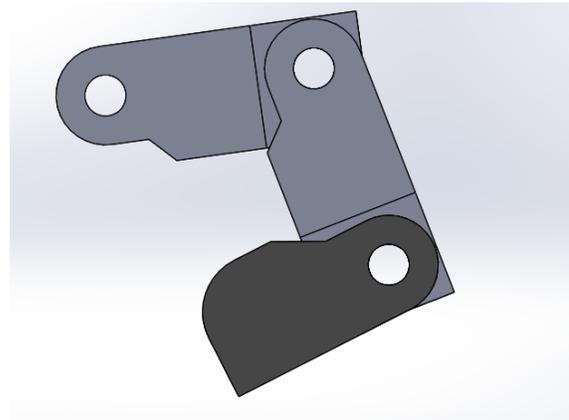


Figure 32: Fully Actuated Finger

4.1.2 Palm Design

The palm's purpose in this assembly is to channel the finger actuation threads and act as a central connection point for the fingers. All the fingers will connect to the palm with 3D Printed joint pins, much like the ones in the finger, but with a longer length. The threads will be run through channels within the palm to their desired destination.

The channels have been designed to not interfere with one another or cause a great amount of friction to dampen the actuation of the fingers. All angles have been designed to be 44 degree or less as not to subject the thread or palm to any unnecessary torque or grinding.

The electronics that are placed in the hand are contained in an assembly called the Palm Cover, pictured below.

The Palm Cover is comprised of a bed and a cover. It will house the battery and the control board that runs the hand. The bed is placed over the back of the palm to divide the Kevlar thread and the electronics. The battery and control board will then be placed on the bed, and then covered by the cover. Two 1.5" screws will be screwed through the cover, bed, and the palm to ensure it will be enclosed.

4.2 Forearm

The forearm in the scope of this project will range from the end of the socket to where the hand is connected. This area does resemble a human forearm and has allowed for simplicity in definitions and comparison between amputees and non-amputated individuals. The forearm will serve the main purpose of housing the mechanics of the hand including servos and their rail system for Kevlar string actuation. These essential components will be housed within an enclosure to preserve the functionality of the prosthesis.

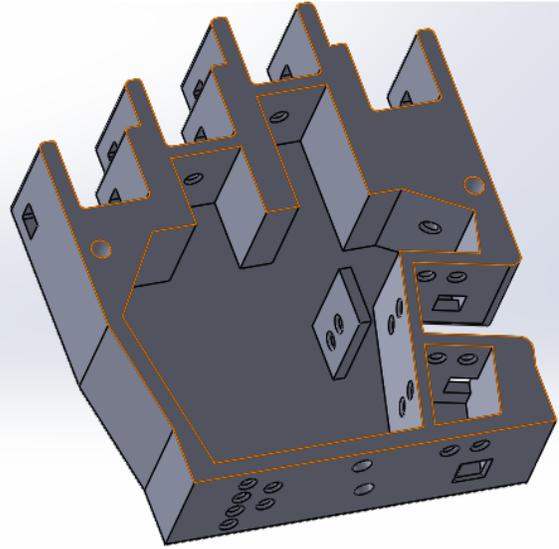


Figure 33: Palm Design

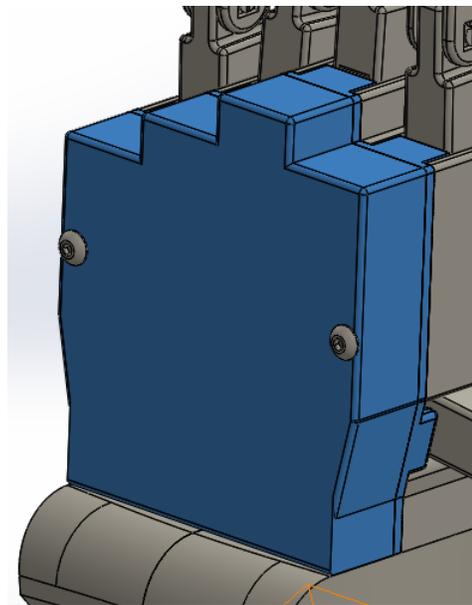


Figure 34: Palm Cover

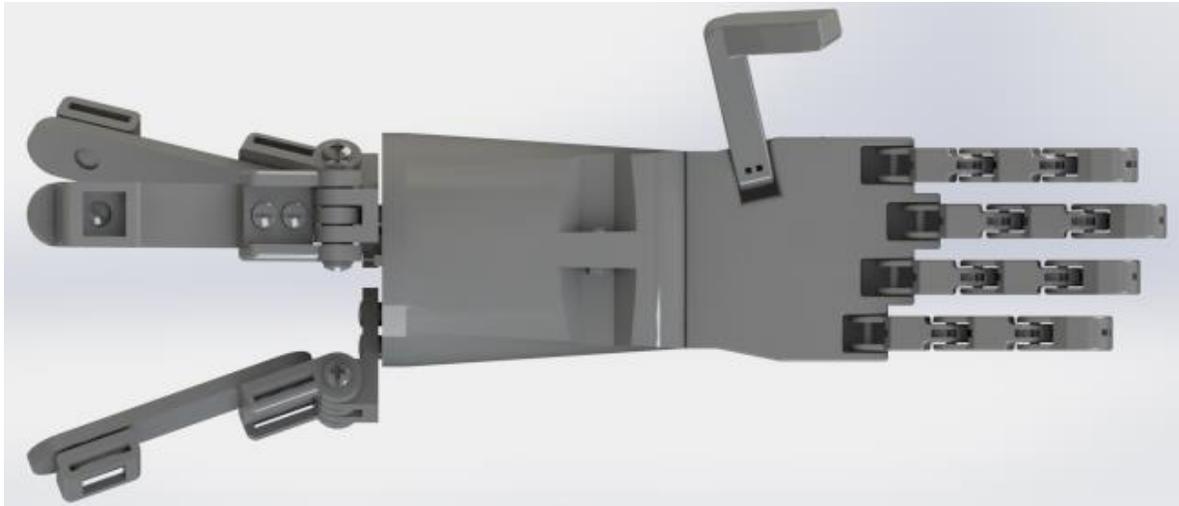


Figure 35: Render of Full Assembly

The servo frame housing has been designed for longevity and robustness. In the design, screw holes are 0.164 inches in diameter to properly fit #8 bolts in this assembly. The servo frame to palm connection will be completed with two bolts tucked inside the servo frame providing the design with stability and a low overall length. The servo frame allows for all four desired finger actuating servos to push and pull cables which travel from the servo rails to the tips of the fingers. These rails, known as cable guides, are fixed to the servo heads and have a 42mm diameter. This size was selected, because it is the smallest diameter which still allows the cable to perform a full actuation with the HS-5585MH motor. The servo housing frame was also specifically designed around these servos, and its main cavity is exactly the size of four HS-5585MH servos positioned side by side. To fit four 42mm cable tracks, the servos alternate sides (left and right) and orientation (up and down). In addition to this, the disks are staggered, the rear two servos sit further out from the center of the frame than the front two. Combining all of these space saving techniques produces what we believe to be the smallest possible forearm for our prosthesis. The servo frame mates with the socket and palm via two #6 screws for each connection.

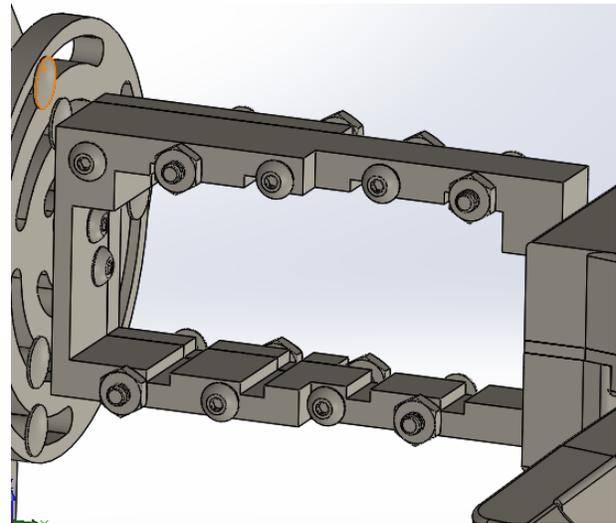


Figure 36: Servo Frame, without Servos

Table 4: Socket Frame Decision Matrix

Socket Frame Decision Matrix		Design Alternatives				
Design Goals	Weighing Factors	Vacuum Suspension	Bladder-Controlled	Compression/Release Stabilized	3D Printed	Mechanically Adjusted
Safety	15	7	7	3	7	8
Ease of Use	14	5	6	4	6	7
Durability	13	5	6	3	5	7
Comfort	12	4	6	1	5	7
Range of Motion	11	8	8	8	8	8
Max Capable Load	10	8	7	8	6	7
Service-ability	9	5	7	5	5	9
Weight	8	5	5	7	7	6
Scalability	7	5	5	8	8	8
Cost	6	5	5	7	9	8
Difficulty to Assemble	5	4	4	7	8	8
Enviro. Factors	4	4	4	5	4	6
Aesthetics	3	5	5	3	7	7
Time to Assemble	2	3	3	3	5	7
Time to Print	1	NA	NA	NA	7	7
	Total	663	722	589	767	890

Note: the design alternatives are not comparable in every category.

4.3 Socket

The socket design alternatives were rated based upon their fulfillment of the project design goals and specifications. Once they were rated and totaled, the highest rated design alternative was selected. The design alternative was benchmarked by existing similar products. Those products were evaluated for possible improvements. The final design concept was generated and a prototype fabricated.

The five alternative socket frame design categories were: vacuum suspension, bladder-controlled, compression/release stabilized (CRS), 3D printed, and mechanically adjusted sockets. These designs were evaluated against the ranked design goals in Table 5. It was decided that the socket frame will be mechanically adjusted and the structural components 3D printed.

The individual parts of the mechanical socket were identified and designed. Figure 38 shows the full assembly of the socket frame. The socket frame parts are: 1 'base plate' (red), 3 'base plate-hinge connectors' (yellow), 3 'hinges' (green), 3 'struts' (blue), 3 'strap retainers' (pink), 3 foam EVA pads, and 2 straps with buckles. These parts work together to provide an easily adjustable, lightweight, sturdy, and comfortable socket frame. Forearms come in many different shapes and sizes. The average forearm has an amorphous ovular cross-section that increases in



Figure 37: Socket Frame CAD Model

size from the wrist to the elbow. Muscular forearms have larger, more toned muscles that increase the girth of the forearm. The change in girth from the wrist to the elbow is also more drastic.

The base plate and base plate-hinge connectors' purpose is to adjust the position of the struts for the girth of the forearm. The base plate has large and small sizes where the hinge-base plate connectors can be attached. This allows adjustment for the girth of the forearm. There are three arcs that comprise two sizes that can be individually altered for each of the three struts. The base plate allows for the maximum adjustments for the individual's comfort and needs. The position of the struts can be swiveled within 90° and the diameter can be changed from 2 to 3 inches.

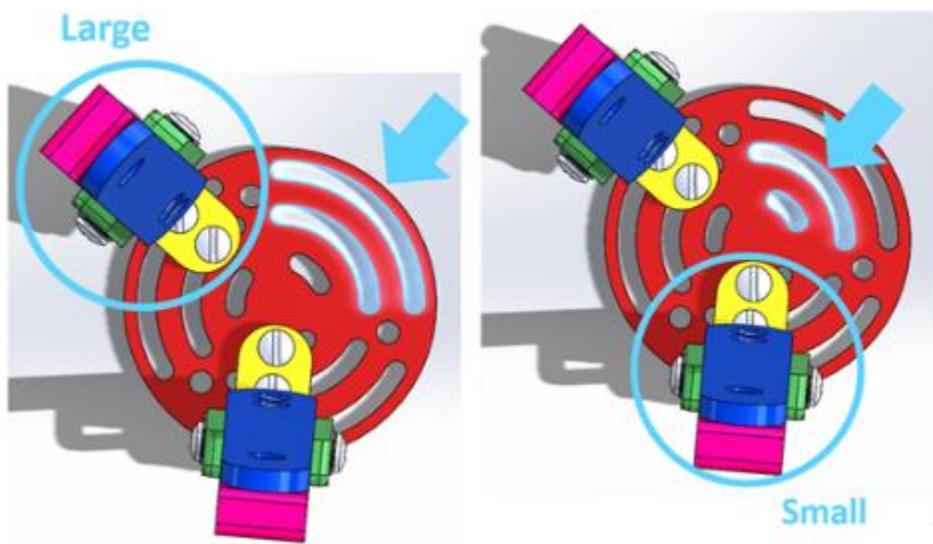


Figure 38: Base Plate-Hinge Connectors' Positions for Girth Adjustments

The arcs also allow for the position and angle of the struts to be changed to the individual's comfort and needs. The three struts are typically positioned approximately 120° from each other. One struts lie on the anterior (top) and two on the posterior (bottom) of the forearm.

The hinges' purpose is to adjust to the angle the strut lies along the forearm. The hinge adjusts so that the socket frame can fit all shapes and sizes. The majority of forearms have a shallow angle and increase minimally in girth when comparing the wrist to the upper forearm. However, the drastic change in girth of muscular forearms creates a steeper angle. The hinge allows the socket frame to adjust to the individual's comfort and needs. The hinge is adjustable from 90° to 180°.

The struts' purpose is to lie flush along the residual limb. Three struts positioned around the residual limb are the main structural support for the rest of the prosthetic. They have an inward compressive force against the limb. This force supports and offsets the weight of the entire prosthetic. It is important for the struts to have a large surface area so that the force is distributed rather than being focused on one part of the residual limb. However, the larger the surface area, the less breathable the socket frame is. An encapsulated socket that surrounds the residual limb completely provides the most force distribution. However, it also has the highest heat retention. It is necessary to find a balance between force distribution and heat retention that is the most comfortable. The struts range in size: the small is 4.5", medium is 6", and large is 8".

The inside of the struts will be lined with super-cushioning high-strength EVA foam. This type of foam is the same as what is used inside football helmets. It is made for the outdoors and is $\frac{3}{8}$ inches thick. EVA foam provides an added layer of comfort.

3D printing with PLA is the best manufacturing process and material for the struts, base plate, hinge, and base plate-hinge connectors. It is a relatively inexpensive material and quick and easy to print more components. It takes 9 hours and 20 minutes to print all 10 of the socket frame components. Once the amputee has learned how to fit, don, and doff a prosthesis, understands their prosthetic preferences, and their residual limb is not swollen or changing shape and size drastically, a more permanent socket frame can be constructed. The semi-permanent frame replaces two of the struts, hinges, and base plate-hinge connectors with carbon fiber struts at the preferred angle and proper girth. The third strut, hinge, and base plate-hinge connector are

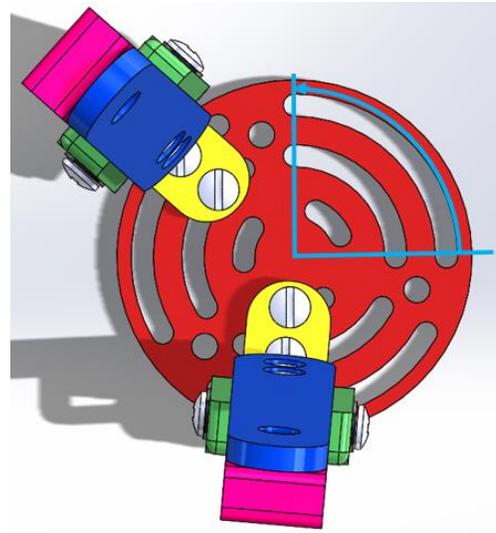


Figure 39: Base Plate-Hinge Connector Angle Adjustment

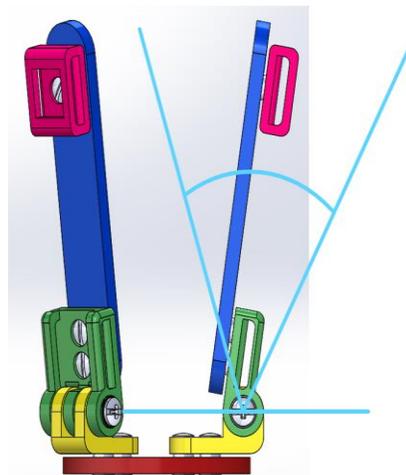


Figure 40: Hinge Angle Adjustment

not changed so that micro-adjustments can still be made. If desired, the third strut can be made of carbon fiber and curved so that it lies flush with the skin.

The socket frame utilizes fasteners and washers. The socket frame 3D printed parts are held together by multiple fasteners. A stainless steel binding post is used as the pin to connect the hinge and hinge-base plate connector together. Philips head screws and low-profile binding posts are used together to allow easy adjustment to the parts. Nylon plastic washers are located along the axes of the hinges to reduce wear. Split lock washers are placed between the Base Plate and Base Plate-Hinge Connector to reduce movement and slippage.

The socket frame is held to the residual limb with ladder straps and ratchet buckles. Ladder straps and ratchet buckles are typically used to secure rollerblades and snowboards. Retainers help to hold the ladder straps in place along the struts while allowing the straps to adjust freely.

An Under Armour compression sleeve or a prosthetic sock is worn under the socket frame. The sleeve is relatively thin so as not to retain heat, provides compression to the residual limb to reduce swelling, and reduces friction between the skin and the socket frame to prevent abrasions. Velcro dots or “Shark Skin”, a product of Martin Bionics, can be added to increase friction between the sleeve or sock to reduce slippage.



Figure 41: Small, Medium, and Large Strut Lengths

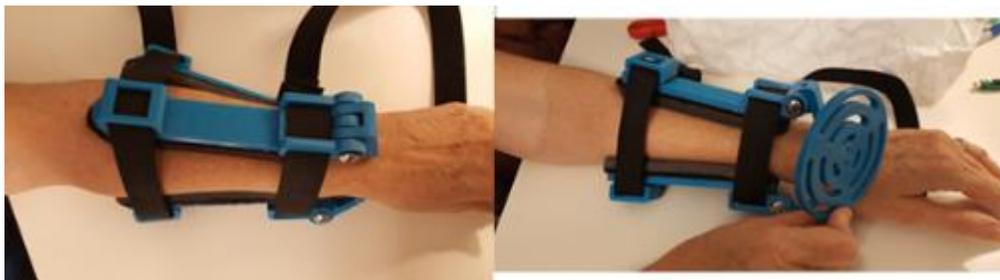


Figure 42: Non-Amputee Showing Strut Positioning

4.4 Motor Selection

A current design constraint for the hand is for it to be capable of holding a jug of milk (around 10lbs/4.5kg) while maintaining the ability to accomplish standard ADLs. The average human finger is around 10cm (3.72in). As such, the torque generated in a worst-case scenario of a 10lb milk jug at the ends of the fingers of this length would be around 595.2 oz-in (~42.8 kg-cm) (torque = length of fingers x force). Furthermore, the torque generated from the fingers themselves (assuming PLA) would be around approximately 4.73oz-in (0.34 kg-cm) ((weight = volume (3.52in³) * density (0.723oz/in³), (torque = center of mass (~1.86in) * weight (2.54oz))), resulting in a total required torque of ~600 oz-in (~43.2 kg-cm).



Figure 43: Hitec HS-5585MH

Based on these calculations, the decision was made to use the Hitec HS-5585MH digital servo (HS-5585MH Economical, High Voltage, High Torque, Coreless, Metal Gear Digital Sport Servo, n.d.). Rated for 17 kg-cm of torque at 7.4V, they provide the needed torque, are quite precise with a rated resolution between 0.079°/μsec to .134°/μsec, and are well reviewed. With a configuration consisting of four motors with the pinky and ring fingers being actuated by the same motor, the system creates 68 kg-cm of torque, allowing for any additional forces to be handled while still achieving the desired load.

4.5 Control System

A prosthetic that requires any sort of input from its user must be intuitively and reliably operable. Intuitive input from the user is currently being pursued in the industry using myoelectric sensors near the location of amputation to pick up signals that would have once controlled the motion of the, now amputated, body part. However, as described in the background, effective myoelectric sensing technologies are currently only available in very expensive prosthetics, and thus budget prosthetic designers usually resort to clunky mechanical and body motion inputs.

The control system developed for our prosthetic aimed to combine very simple myoelectric and mechanical inputs with dynamic force sensing technology in order to provide the user with a simple yet effective interface with their prosthetic. In short, the user need only select the type of grip they desire and send a myoelectric signal to begin performing that grip. Force sensors located on the fingers and palm of the hand take care of how much force the hand will apply to the object being gripped and will dynamically adjust this force to avoid failure of slippage. The user then need only send another myoelectric signal to tell the hand to open. This section outlines the design and components of various blocks within our proposed control system. A view of the entire system can be found in Appendix E.

4.5.1 DC to DC Converter

The power requirement for the servos used in this project called for 7.4V batteries. However, the microcontroller used requires an input voltage of 5V, so it was necessary to design a DC to DC converter to bring the voltage from the battery down to an acceptable level. The LM1084 voltage regulator is a low dropout IC that has the ability to output a steady 5V with the right voltage divider applied across its ground. The datasheet indicates that the output is determined by the following equation:

$$[1] \quad V_{OUT} = 1.25V \left(1 + \frac{R_2}{R_1} \right)$$

Using resistances of $R_2 = 330\Omega$ and $R_1 = 1k\Omega$ in equation (1) results in a V_{OUT} of 5V. The input to the converter is a female barrel jack and there are capacitors between Vcc and GND to act as filters. Finally, a small LED is used to indicate that the device is on. The schematic below shows the schematic for the complete converter.

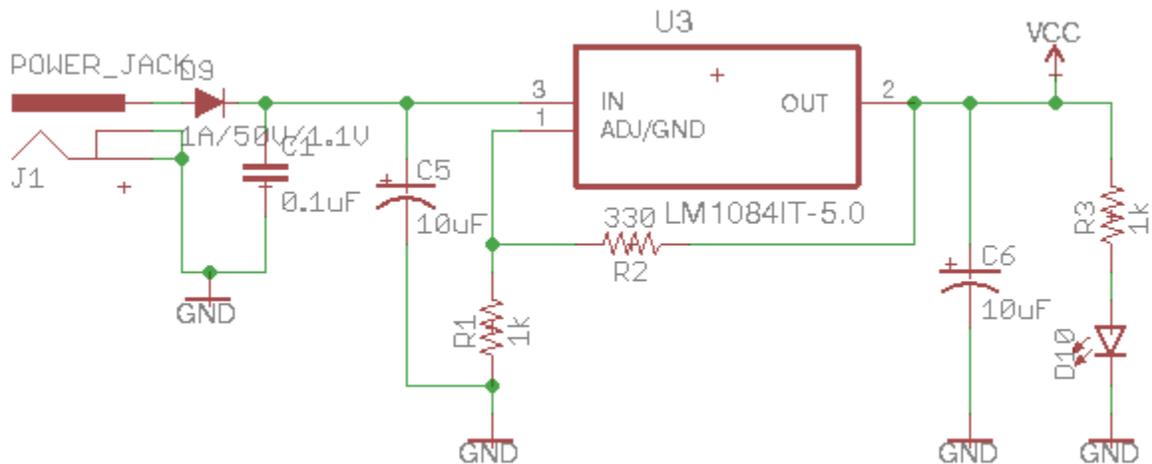


Figure 44: Converter Schematic

4.5.2 Myoelectric Input Block

The control system calls for two easy to produce signals from the user to denote a desire to close the prosthetic hand and then to reopen it. It is not necessary for the system to interpret what grip the user desires as that will be handled by a mechanical input described further in the report. The MyoWare Muscle Sensor is a prefabricated PCB that contains the necessary hardware to translate small variations in voltage in a muscle into analog values that can then be read by a microcontroller. Our control system uses two Myoware sensors placed on the flexor muscles of the upper forearm.

The MyoWare Muscle Sensor receives its signals from electrodes that are in direct contact with the user's skin. There are many different types of electrodes, but this design will focus on multi-purpose medical electrodes and conductive fabric. It is best that the electrodes receive a strong, clear signal. This can be achieved by maintaining skin-to-surface contact, receiving minimal noise and interference, and having a high conductivity. Prototyping of the muscle sensor consisted solely of the use of electrodes as they provide a much clearer signal compared to conductive fabric.

The schematic shows a 6-pin configuration for the myoelectric sensors. Two pins are used as power, two are used as ground, and A1 and A2 are the respective analog output for each sensor.

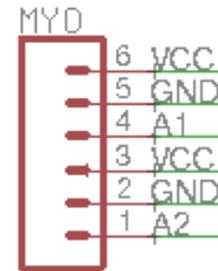


Figure 45: 6-pin configuration

4.5.3 Grip Selection

The second component that assists in user input is the grip selection block of the control system. Using a rotary encoder, the user can quickly scroll to the desired grip they wish to perform. When idling, the display will show the current grip that will be performed if a signal is received from the user. Turning the encoder causes the display to show all the available grips mapped as numbers between 1 and 5. The user need only push down on the dial after scrolling to their desired grip and the display will hold that grip for execution.

The grips were mapped as thus in accordance with the possible finger positions described in Section 4.1.

Table 5: Finger Positions

Grip #	Grip Name	Grip Description
1	Rest	For use when hand is not in use, fingers slightly curled
2	Point	All fingers closed except index (thumb closes last)
3	Rod Grip	Four fingers closed, thumb does not move
4	Pinch Grip	Index, middle, and thumb finger meet
5	Spherical Grip	All five fingers close together

Figure 46 below shows the schematic for the grip selection block. The rotary encoder is modeled as a potentiometer that feeds an analog signal into the microcontroller. The display is modeled as a common anode display driven by a BCD to seven-segment decoder. The decoder minimizes the amount of pins necessary to drive the pin-heavy display by decoding a four digit binary signal. Resistors are used to limit the current flowing into the display so as to not burn out the LED's inside the display.

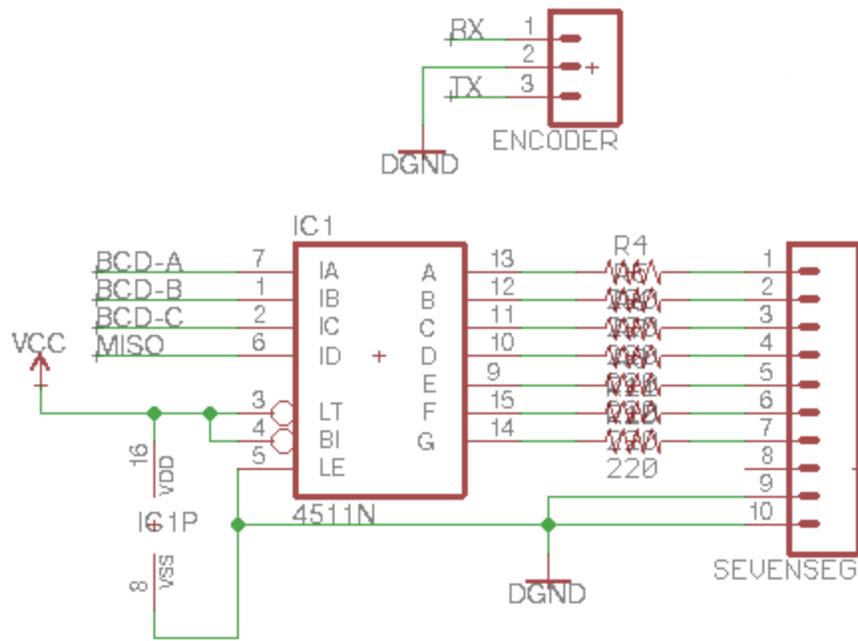


Figure 46: Grip Selection Block Schematic

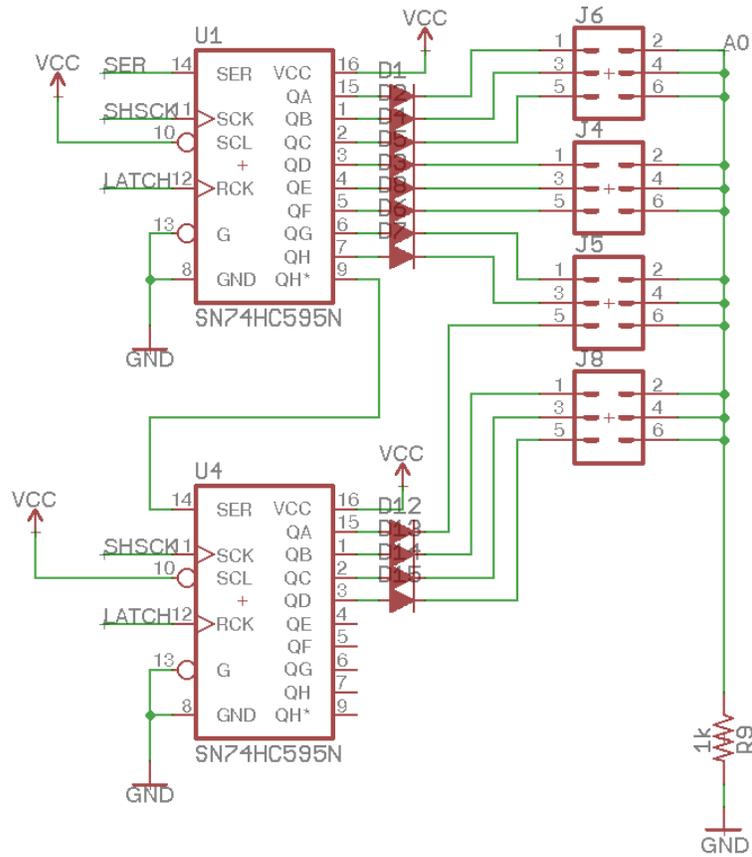


Figure 47: Force Sensor Array Schematic

4.5.4 Actuation Feedback Block

It was necessary to design a method for gathering force data on the hand for the microcontroller to make decisions on actuation. Without such feedback, the motors driving the fingers would simply actuate as much as possible and stall when the fingers cannot move any longer. This does not allow for fine motor control, which would not be beneficial if the user wanted to, for example, shake someone's hand.

The actuation feedback block of the control system uses a series of force sensitive resistors that are placed all over front of the palm and fingers. These resistors, when squeezed, allow additional voltage through them, and this difference in voltage can be measured by a microcontroller. In order to interface with the necessary amount of force sensors to cover the whole hand, shift registers were utilized to cycle through and read each resistor one at a time. This process of reading each resistor takes only about 100ms (or 1/10th of a second). The advantage of this circuit is that it only requires a few digital pins to run the shift registers and one analog input for all of the resistors.

The schematic below shows the final construction for the force sensor array. The three 6-pin connectors labelled J4, J5, and J6 are where the force sensors will be connected.

The microcontroller can use the force sensor to determine if the servos need to be turned more or if they can be locked in place. As long as the user does not send an open-hand signal, the force sensors will stay active, checking if more force is needed from the servos to maintain a firm grip. Twelve resistors are used to effectively cover the area of the hand and are arranged as pictured in Figure 48.



Figure 48: Sensor Placement

4.5.5 Servo Control Block

Due to the decision to use servos as opposed to other forms of actuation to actuate the hand, this block of the control system is very simple. Servos have a built-in microcontrollers as well as position tracking that can be interfaced with using only a serial data signal. This means that the setup of the servo control block simply consists of supplying power to the servos at their rated voltage and connecting the servo digital pins to the microcontroller. The servos can be moved using a system called pulse width modulation (PWM). PWM refers to the concept where short, measured bursts of voltage are used to encode specific control signals. For example, these servos will move to their center position when a 1.5ms pulse is sent. The schematic for this block can be seen below.

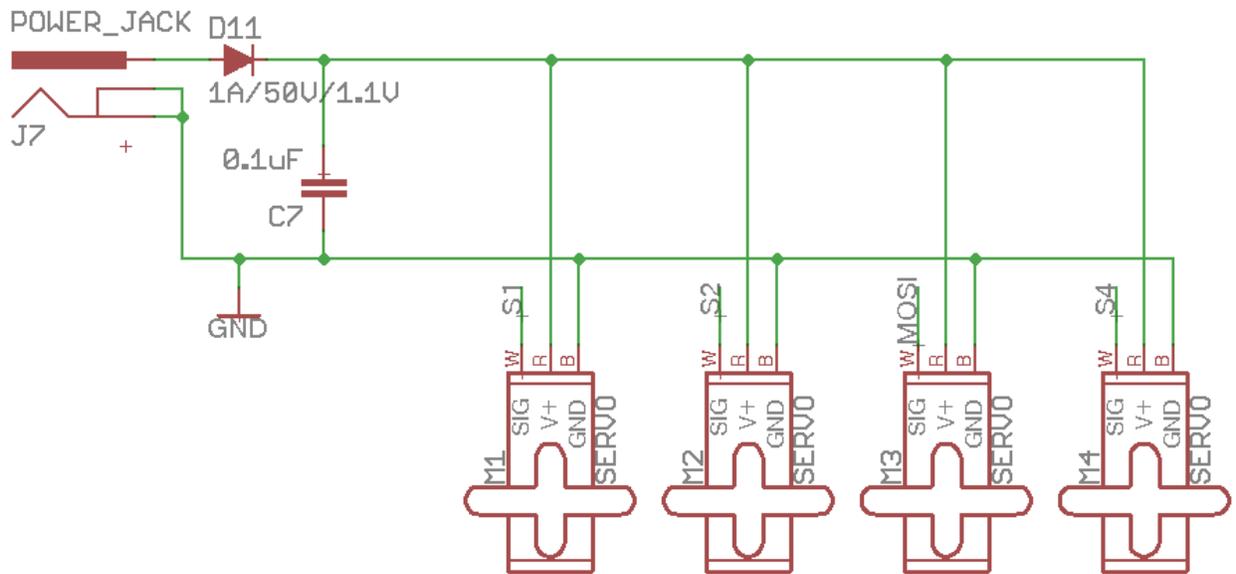


Figure 49: Servo Control Block

The servo's chosen for this block require 7.4V, which became the constraining voltage for the entire system. It is also important to note that the ground for this block, as well as all other blocks, is shared with the microcontroller. This allows both processors in the servo and the microcontroller to see the same signal when messages are passed between them.

4.5.6 Microcontroller

Once all of the components of the control system were determined, the decision for a microcontroller was made based on power requirement and number of inputs and outputs available. By using decoding and multiplexing techniques in both the actuation feedback and grip selection blocks, the overall amount of pins necessary to handle all of the blocks was minimal. Thus, the ATmega328P was chosen due to its ability to use a 16MHz clock and its relatively low power requirement.

A large portion of control is being performed by the microcontroller in the form of constantly looping code that takes input from the three input blocks and outputs the corresponding signals to the servo control block. The flow diagram for this code can be seen below. It effectively consists of a phase of three states: a calibration state, an idle-open state, and an idle-closed state. The calibration state is described in the section below. The idle-open state waits for a myoelectric signal to start closing the fingers, and begins actuating the fingers when the signal is received. The code then moves into the idle-closed state where it continuously determines whether there is a solid grip being applied to an object or if maximum actuation has been reached. While it is checking the force sensors, it also waits for a signal to move back into the idle-open state. When this signal is received, the motor are instructed to actuate in the opposite direction, opening the hand to its full extension.

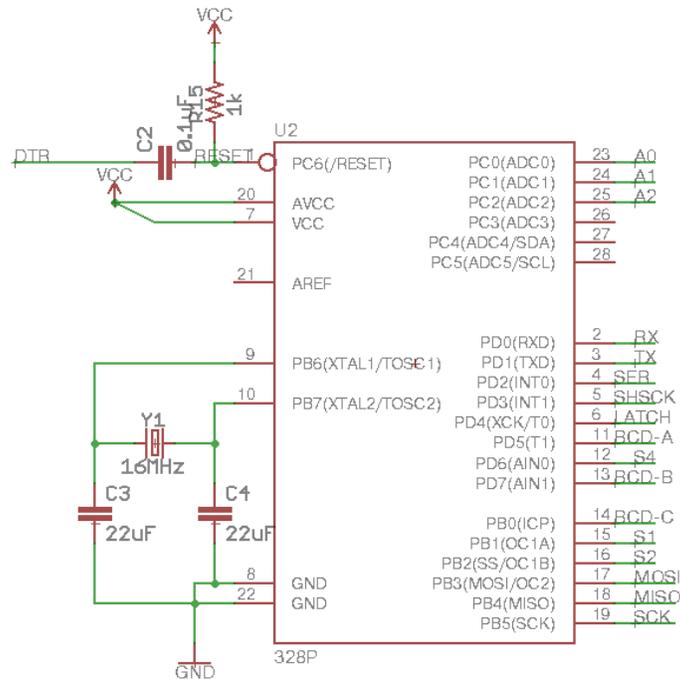


Figure 50: Microcontroller

The code as a whole operates on an interrupt-driven 100Hz clock. Each time an interrupt occurs, the interrupt service routine (ISR) sets Booleans that act as triggers for the sensors to be polled and an appropriate action based on the state machine described above in the main loop to be taken, individually. Polling the sensors involves reading and storing the values read from each force sensor and the Myoelectric sensor. These are then used for determining the active state's action. For the idle-open state, the Myoelectric sensor is used to determine if the hand should start closing. Also, during this state, the rotary encoder is being polled to determine which grip will be selected once the Myoelectric sensor value threshold has been exceeded. During the closing state, the force sensor readings are used to determine if an object is either blocking or in the grasp of a finger and that finger should stop moving. This is accomplished by writing each servo a maximum of five degrees further towards its desired state from the previous state until the finger's respective force sensor reaches its threshold reading or the finger reaches its desired

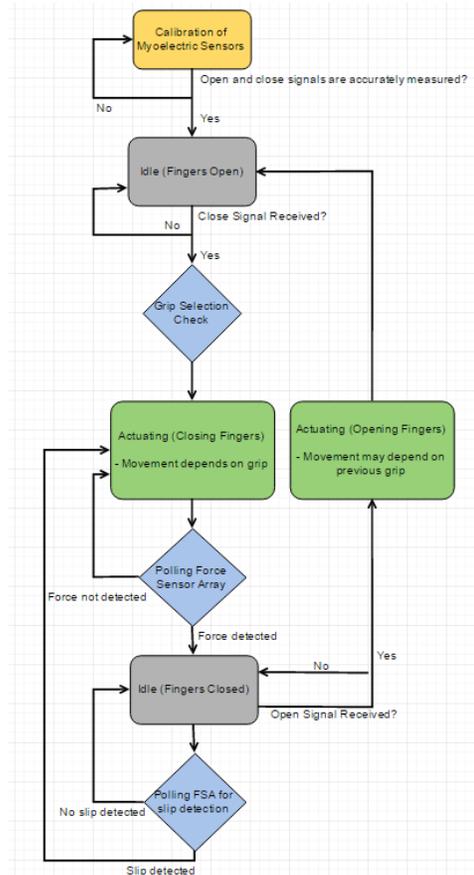


Figure 51: Logic Flow Chart

position. Once one of these conditions are met, a Boolean is set stating that the finger is finished moving. This is both used in the event of the thumb/fingers moving asynchronously due to the requirements of the grip as well as to move to state 3, idle-closed. The idle-closed state acts very similarly to the closing state in that the servos are still told to move in order to adjust for slip from grasped objects. The primary difference is that another “high” reading from the Myoelectric sensor will cause the fingers to open and the state to change to idle-open once the fingers are open.

4.5.7 Battery Selection

In order to drive all the electronics, an appropriate power source must be selected. It needs to have enough voltage to drive the servos as well as enough charge (measured in mAh) to power all the electronics for an extended period of time. In particular, the battery needs to be rated for 7.4V and have enough charge to last through a day of standard usage. In order to determine this, amperage values for different states of the finger servo were measured and labelled below as Idle (no motion), Stall (servo is attempting to move but cannot), and Average (servo is moving with varying force applied). The amount of time the servo could operate within these three states was calculated for two different battery. The amount of time four servos could operate was also calculated to mimic the actual use case within our system.

Table 6: Estimated Battery Life Based on Servo Power Draw

		Current Draw		
Battery	Amount of Motors	Idle ~ = 5mA	Stall ~ = 2500mA	Average ~ = 200 - 1000 mA
5000mA-hr LiPo Battery	1	1000 hours	2 hours	25 hours - 5 hours
	4	250 hours	0.5 hours	6.25 hours - 1.25 hours
4600mA-hr LiPo Battery	1	920 hours	1.84 hours	23 hours - 4.6 hours
	4	230 hours	0.46 hours	5.75 hours - 1.15 hours

Appendix C.2 indicates that on average a person will use their hand to perform basic ADL’s for about 5 hours and 6 minutes every day. The following calculations determine two different mA*hr ratings using Idle and Average amperages:

$$\begin{aligned}
 [2] \quad m\text{Ahr Needed} &= (\text{Hand Idle Time} * \text{Idle Current Draw}) \\
 &\quad + (\text{Hand In Use Average Time} * \text{Average Current Draw}) \\
 [3] \quad m\text{Ahr Needed (Min)} &= (19\text{hr} * 5\text{mA}) + (5\text{hr} + 200\text{mA}) = 1095\text{mAhr}
 \end{aligned}$$

$$[4] \quad mAhr \text{ Needed (Max)} = (19hr * 5mA) + (5hr + 1000mA) = 5095mAhr$$

If the maximum average current is used, the amount of mA*hr necessary is just above the rating of the first battery, and this isn't accounting for when the prosthetic is off at nighttime. However, it became necessary to choose a smaller battery due to size constraints of our prototype. As such, the lower mA-hr battery was chosen for our prototype.

4.5.8 Myoelectric Data Processing

The ultimate goal of the data processing steps applied in this project is to accurately predict the user's desired action and act accordingly. A Kalman Filter is used to filter the incoming data which is then sent to an expectation maximization algorithm, a form of data clustering algorithm, to accurately determine the user's input. After being sent to the EM algorithm, the data is clustered based on its sensor value and change in sensor value to determine if the user has the corresponding muscle relaxed, flexed, or if he/she is in the process of flexing or relaxing. This is then sent to the state machine to generate an appropriate output. As an example, if the algorithm determines the user is starting to flex with the hand in an open position, it would start to close the hand.

The first stage of the data processing cycle is a Kalman Filter. The signal from Myoelectric sensors is inherently noisy. This, in turn, can make predicting the user's actions more difficult at a single point in time or requires sampling and averaging over 100-200 milliseconds (ms) period of time. A way to circumvent this problem is through filtering the stream of data. As such, a position-velocity (PV) model Kalman Filter was implemented as a software filter for this purpose. "A Kalman filter is an optimal estimator - i.e. infers parameters of interest from indirect, inaccurate and uncertain observations.... [It is optimal in the sense that if] all noise is Gaussian, the Kalman filter minimizes the mean square error of the estimated parameters" (Kleeman, n.d.). As seen in Figure 52, the Kalman Filter smooths the sensor data quite well while representing that data relatively well.

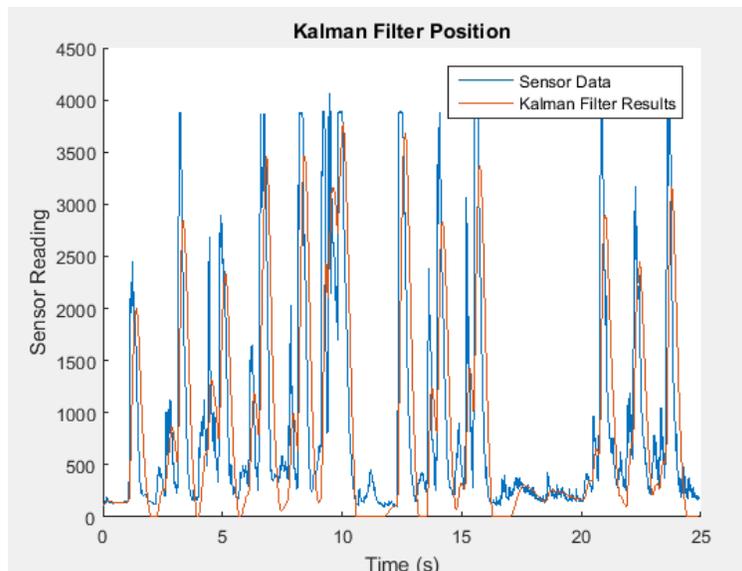


Figure 52: Kalman Filter on Muscle Sensor Data

Once run through the Kalman Filter, this data is then analyzed to create a mixture model, a mathematical (probabilistic) model of distributions within a given dataset or input. From this point, the data is then fed into an Expectation Maximization (EM) algorithm based on the mixture model in order to cluster the data into categories of predicted actions. Particularly, the algorithm utilizes two clusters: a Gaussian-based one representing the relaxed state and an exponential-based one representing the flexed state. This is done in order to allow for greater prediction capabilities than merely setting arbitrary thresholds for given actions. Furthermore, it creates an effective way of calibrating the hand to the user when combined with a calibration process when the hand is first used. The results of an early EM prototype can be seen in Figure 53.

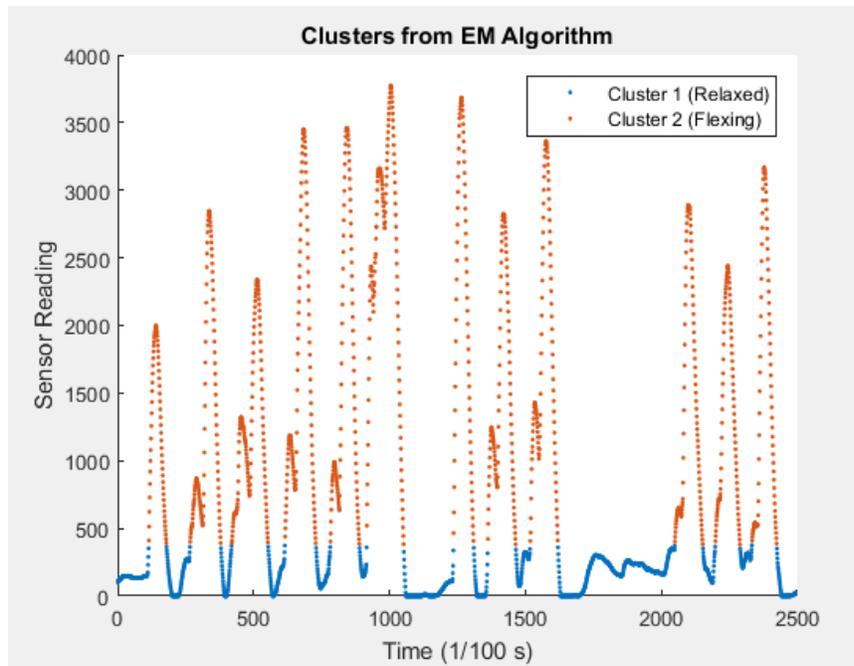


Figure 53: Results of Early EM Algorithm Prototype on Filtered Sensor Data

5. Testing and Results

5.1 Tests

In order to assess the functionality of the team's prosthesis, several tests were developed and carried out. Each test had a specific parameter it was assessing, and the standards and goals were drawn from the product specifications. The prosthesis was tested as a system, its individual components were tested when necessary. For full test procedures, see Appendix F: Full Test Procedures.

5.1.1 Pin Fracture

The objective of this test is to determine whether the pins placed at the finger joints were able to allow full motion of finger and hold the required load without failing. The load the pins in the joints and hand will have to withstand a maximum load of 11lb +/- 1lb. The goal of the prosthetic hand is to allow a user to be able to complete most activities of daily living. Through research it was found that most activities can be completed by being able to lift 11 pounds. If the pins are able to hold up to 11 pounds then that would mean the pins are successful and can be used within the prosthetic.

5.1.2 Thread Ductility

The objective of the test is to determine at what weight the Kevlar thread would deform. The Kevlar threads are what allow the hand to actuate. They need to be able to withstand the forces that will be placed on the fingers and hand. All the fingers together will pick up objects, but to ensure the hand will be able to hold any object the fingers will be tested individually. The Kevlar thread needs to be able to support at least 11 pounds. The test is also done to determine how long before the Kevlar will deform and elongate. When the Kevlar thread elongates it makes it more difficult to pull on the thread with the servo. It is important to understand when the thread will deform and when it needs to be serviced.

5.1.3 Hand Friction

The 3D printed hand must be capable of withstanding the wear and resisting the friction the user subjects it to. The hand includes all pins, finger components, palm assembly, and the O-rings that aid actuation. Understanding how the hand will respond under repeated and continuous movement will determine if the hand is ready to be used in the final assembly as it is designed. Failure to withstand the wear means a redesign will be necessary.

The objective of this test is to determine whether the hand will be able to withstand continuous and full actuation. The test will be ran for 600 cycles for a fingers. One cycle is defined as the finger actuating from its open position to its closed position and back to the open position. The classification of success and failure is described below.

5.1.4 Socket Slippage

The objective of this test is to measure the slippage of the prosthesis on the arm. To simulate normal loading and unloading during daily use, the prosthesis will be affixed to a model of a residual limb as if it were an actual amputee's arm and tightened securely. Hanging masses will be hung from the prosthesis for one minute. Multiple angles will be tested. The starting and ending positions of the prosthesis will be marked and measured. A Likert Scale will be used to rank the level of success or failure after the five minutes have passed.

To test the slippage of the socket, the socket will be attached to the model of the residual limb at one of three test angles: 0 degrees (horizontal), 45 degrees, and 90 degrees (vertical). Hanging masses in the form of pre-weighed volumes of water are to be hung from the fingers. Marked slip distance after one minute of testing will be measured with calipers that have been calibrated properly.

To test slippage on human skin, the socket portion of the prosthesis with the base plate removed can be worn on an actual human arm. The same test masses can be hung and the test can be repeated.

5.1.5 Finger Actuation

The objective of this test is to determine if the design of the finger was able to complete the full motion required to complete desired activities. The test will see if using the developed program the fingers will be able to open and close. The amount of friction will be tested between the joints to ensure there is enough room for each joint to open and close. The servo will also be tested to see how many cycles it can withstand before any complications arise. The different components will also be tested to see when they need to be serviced. Where the thread is attached to the servo can deteriorate over time and will be observed to see how many cycles it can withstand before breaking.

5.1.6 Control System Hardware

The objective of this test is to verify the functionality and power specification of the electrical system that actuates the prosthetic. All blocks within the system must be able to function simultaneously from the same power supply and under maximum current draw. The test will explore every possible usage of the system and determine whether it is acting in accordance with its proposed function. The tests within this section are separated into software and hardware tests in order to isolate errors.

5.1.7 Control System Software

For the prosthetic to function properly, each individual system needs to function in of itself as well as a whole. Since the prosthetic is controlled by software, this software needs to be tested to ensure this functionality. The code written must be robust, reliable, and relatively bug-free while interacting with the other physical systems within the prosthetic effectively.

The objective of this test is to determine if the written software and control systems can appropriately operate each part of the prosthesis. The software must be able to interact with the mechanical and electrical systems. These tests explain various tests to ensure the integrity of these interactions.

5.1.8 Hand Functionality

The objective of this test is to assess the functionality of the prosthesis' pre-programmed grips and gestures. These are: Open Hand, Closed Hand, Point, and Pinch. To do this, a scale of 1-7 is used to determine how well the prosthesis accomplished an assigned task, with 7 being success and 1 being failure.

For this test, the prosthesis should be either secured to a test subject's arm (note: the base plate should be removed if the subject does not have a residual limb), or to a model of a residual limb. Once secure, the prosthesis will be tested using the procedures and objects outlined below. Each grip/gesture is to be tested with different objects as appropriate.

5.2 Test Results

Below is the results of the test procedures carried out by the team. Each section notes a different test procedure, the results, and the notes taken throughout the test session.

5.2.1 Pin Fracture

The Pin Fracture test, Appendix F.1, was designed to ensure that the pins used in the joints could withstand the load of weight up to 10 lb. The test was run by placing a finger segment fully assembled, with a pin and washers to recreate the application as best as possible, in an Instron machine. The assembly was tensioned until failure. The test was marked a success as the pins tested far exceeded the 10 lb. requirement. The results can be found in Appendix F.1.

5.2.2 Thread Ductility

The Thread Ductility test Appendix F.3, was designed to ensure that the Kevlar thread would not elongate and plastically deform to a length that would cause the finger to be unable to actuate completely with the strength it was designed to perform. The test was run by hanging 10 lb. from the end of three lengths of thread and measuring the original and then the elongation. The test was marked a success as the thread did not elongate more than 3%. The results can be found in Appendix F.3.

5.2.3 Hand Friction

The Hand Friction test was designed to ensure that the hand used in the prosthetic did not wear down to inoperable dimensions. The test was run by measuring each component used in a finger, actuating the finger through 500 cycles and remeasuring the dimensions. The components could not wear down more than .05 inches from its original measurement. The test was marked a success as all components fell into the range they are deemed as functioning.

5.2.4 Socket Slippage

The Socket Slippage test, Appendix F.4, was designed to ensure that the socket used in the prosthetic was functioning as designed. The test was run by monitoring how far the socket

would slip down the stump when exposed to weight at varying angles. Readings were taken with a pair of calipers as weight was increased up to 10 lb. The test was marked a success as the socket did not slip past the limit of 15 cm. The results can be found in Appendix F.4.

5.2.5 Finger Actuation

The Finger Actuation test, Appendix F.2, was designed to ensure that the finger designed in the prosthetic actuated properly. The test was run by actuating the finger using the designated servos. The angle was measured of each component to ensure the finger actuates evenly and completely. Additionally, the finger was required to actuate within 2 seconds to be deemed responsive and capable of normal grip function. The test was marked a failure as the fingers were not actuating properly. The fingers have worked in the past but an assembly error was made prior to the test with the threads that caused the failure. The test was re-run and passed the test. As the failure was due to an assembly error, the team has deemed the test an overall failure as repeatability of the passing run may not easily be repeated by users.

5.2.6 Control System Hardware

The Control System Hardware test, Appendix F.5, was designed to ensure that the hardware used in the prosthetic was functioning as designed. The test was run by monitoring each port of connection in the hardware. Readings such as voltage, current, and signaling were taken. The test was marked a success as all connections and readings fell into the range in which they are deemed as functioning. The results can be found in Appendix F.5.

5.2.7 Control System Software

The Control System Software test was designed to ensure that the software code used to control the prosthetic as designed. The test was run by monitoring each function of the code so that it communicates and controls the appropriate component of the prosthetic properly. Observations of the input, output of both the electrical and physical hardware were taken to determine if they were successful or have failed.

5.2.8 Hand Functionality

The Hand Functionality test, Appendix F.6, was designed to ensure that the hand used in the prosthetic could complete the actions it was designed to do. The test was run by actuating the hand through different grips patterns, holding daily-use objects such as doorknobs and water bottles, etc. The hand must complete all these functions and tasks to be considered a success. The test is currently marked incomplete, which deems the test a failure. This is due to the fact that finger actuation was ultimately deemed a failure due to repeatability concerns. The team believes with the right preparation that the test would succeed but did not find it possible for users to repeat the actuation success that was necessary to pass the functionality test.

6. Project Expansion and Continuation

Over the course of the project, this MQP Team has designed a functional socket, forearm servo housing, hand, and fingers from the ground up. Best practices from previous projects were adapted where necessary. As a system, the goal up to now was to prove that the team's designed system can operate appropriately, opening and closing the fingers at the user's input. The prosthesis will open its fingers, and then close around an object until the force sensors trigger, causing the fingers to stop.

However, throughout this entire process many other features to implement for the prosthesis were considered and in some cases thoroughly explored. Most of these features seek to create a prosthesis that more closely mimics the functionality of a real hand. Prototype implementation and testing of these features was not carried out due to time and specification constraints.

6.1 Haptic User Feedback

"For a myoelectric prosthetic user, efferent signals [haptic feedback, in other words] on the residual limb are used to control the prosthesis; however, the prosthetic device does not compensate for the loss of afferent signals. This requires the amputee to rely on vision alone for precise control of the prosthesis reducing the effectiveness and speed at which it can be operated. ... The importance of incorporating a sensory substitution device in a prosthesis is becoming increasingly essential as more functional hand prostheses are being developed with multiple degrees of freedom (DOF) as compared to 1 DOF basic gripper prostheses" (Erwin & Sup, 2015). As such, a concept in development for this project is using air-filled sacks that vary in pressure depending on the amount of force detected by force sensors in several locations on the hand. Depending on which sensors detect changes in force, corresponding sacks will inflate or deflate in response. The air sacks themselves would be placed along the arm similar to a blood pressure cuff. Small fish tank air pumps would be used to inflate these air sacks along with solenoid driven release valves to reduce pressure once the force sensors no longer detect force along the hand. Overall, this system is meant to give the user a sense of feeling based on what the prosthetic hand is experiencing.

6.2 Cooling

A 2001 study of nearly 100 amputees found that heat and perspiration inside the socket were reported by 72% of the survey participants as the most common cause for a reduced quality of life. Removing perspiration from the surface of the skin and developing an active cooling system that is capable of reducing residual limb temperature to decrease perspiration and increase socket comfort⁷², are necessary for prosthetic sockets.

Four alternative cooling system designs were identified: fluid, computer central processing unit (CPU) fans, CPU fans combined with a heat sinks and peltiers, and open frame socket. These

⁷² Farrell, 2016

designs were evaluated against the ranked design goals in Table 7 below. It was decided that the best cooling system is CPU fans followed closely by CPU fans with heat sinks and peltiers. Open frame sockets aren't really a method of cooling but that they are cooler than typical sockets because they don't retain as much heat. Therefore, all three of these methods will be tested and compared.

Table 7: Cooling System Decision Matrix

Cooling System Decision Matrix					
Design Goals	Weighing Factors	Design Alternatives			
		Fluid	CPU Fan	CPU Fan, Heatsink, & Peltier	Open Socket
Safety	16	7.5	8.5	6.5	9
Ease of Use	15	8.5	10	10	8
Durability	14	7	10	10	10
Comfort	13	8.5	5	8	6
Range of Motion	11	7.5	9	9	9
Max Capable Load	10	NA	NA	NA	NA
Service-ability	9	3	8	7	8
Weight	8	1.5	9	8	7
Scalability	7	7	10	10	10
Cost	6	3	8	5	5
Difficulty to Assemble	5	3	9	8	5
Enviro. Factors	4	10	5.5	7.5	8
Aesthetics	3	NA	5	5	7
Time to Assemble	2	3	9	7.75	5.5
Time to Print	1	NA	NA	NA	5
	Total	674	918.5	890	870

Note: The decision is based upon unknowns and the design alternatives are not comparable in every category.

An option to supplement or replace the Open Socket design is through the use of computer central processing unit (CPU) fans. This design is in the comparison phase. CPU fans would act as an active form of cooling to further cool areas of contact that the Open Socket would otherwise

not cool as well due to its passive nature. One or more CPU fans, depending on the size of the fans and space constraints of the afflicted area, would be placed along areas deemed to be “high heat” areas. Certain areas result in more heat and friction and could use supplemental cooling.

CPU fans could, in themselves, also be supplemented through the use of peltiers. Peltiers operate on the principles of thermoelectric cooling. “All electric current is accompanied by heat current (Joule heating). What [Jean] Peltier [discoverer of the Peltier Effect] observed was that when electric current passed across the junction of two dissimilar conductors (a “thermocouple”) there was a heating effect that could not be explained by Joule heating [heat being generated from electricity passing through conductors] alone. In fact, depending on the direction of the current, the overall effect could be either heating or cooling. This effect can be harnessed to transfer heat, creating a heater or a cooler”.⁷³ This concept creates a temperature differential across the device. One side gets hot while the other gets cold. Due to this, peltiers could be used in conjunction with CPU fans and heatsinks in order to cool the user’s limb and remove the heat from the peltier. This design is in the comparison phase.

The concept of thermoelectric cooling has also been used in a design by Leto Solutions for a prosthetic leg.⁷⁴ Though likely different in execution from what this project’s arm would likely require, this shows the viability of the use of the technology. However, how well the Open Socket reduces the amount of heat experienced by an amputee will need to be further explored to determine the necessity of either CPU fans or peltiers.

6.3 Wrist

In our design the wrist would not be in the location of a typical human arm, rather it would be fairly close to the site of a transradial amputation. The location of actuation has been intentionally relocated to mitigate the complications that would result by having stationary servo motors operate rotating fingers.

A system to have the arm be able to rotate 180 degrees will be created and connected to the forearm servo housing and the wrist servo housing. The system that would be implemented is a planetary gear system and a servo. The planetary gear system will use spur gears that will have a ratio of 3:1 from ring to sun gear and will have an external diameter of two inches. The outer diameter of the largest component, the socket frame, is currently three inches. Therefore, the system that will be used to turn the arm should also be roughly the largest diameter there currently is. It must be able to rotate the prosthetic while at the same time meeting its size requirement.

When selecting a servo for wrist rotation, as with the finger motors, the goal is to have the capability of moving around 8-10 pounds, or approximately the weight of a gallon of milk to meet the requirements we set. As such, the dimensions of a milk jug in order to accurately determine how where the center of gravity is of a milk jug and how much torque would be exerted on the arm from it, determined to be a minimum of 400 oz-in of torque. This would require the use of a gearbox to amplify the torque of the selected motor. A drawback of using this in conjunction with

⁷³ Understanding Thermoelectric Cooling, n.d.

⁷⁴ Pace, 2014

a servo, though, is the fact that a servo's range of motion is generally limited to between 180-360 degrees, depending on the servo. Using the gearbox would further reduce this range of motion and would likely result in not being able to achieve a full 180-270 degree rotation to mimic a human wrist. To circumvent this problem, a continuous rotation a possible servo was selected to be used.⁷⁵ A continuous rotation servo was chosen due to the fact that the gearbox would limit the maximum amount of rotation achievable by a normal servo. This motor will then be mated in a 3:1 ratio gearbox to increase its torque to the needed amount.

Though by moving the wrist up the forearm the group has removed many issues, one still exists - the muscle contraction sensing wires will have to remain stationary on the user's muscle, while rotating along with the prosthetic as the wrist is turned. A solution the group is considering for this problem is a conductive track which runs around the circumference of the prosthetic to allow for a stationary muscle contraction wire to be in constant contact with the moving arm.

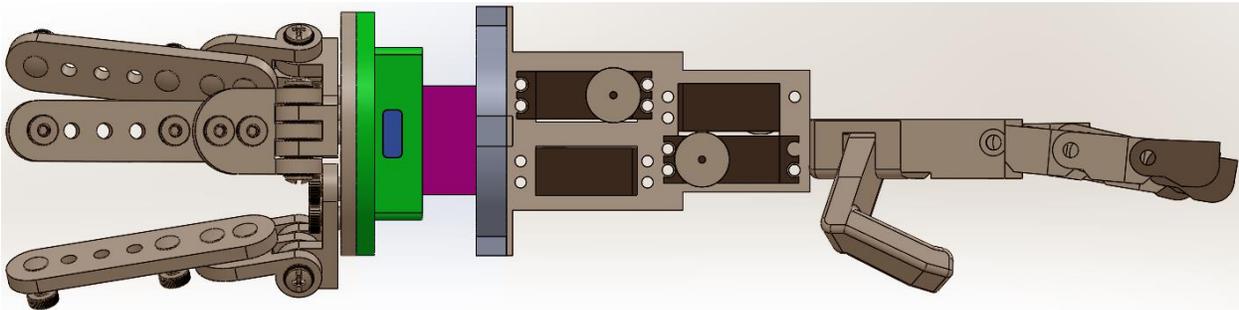


Figure 54: Possible design for wrist

6.4 Scalability

Equations and Relations is a powerful tool SolidWorks provides to its users. It is a duty of the team to harness the power of this feature and make use of its functionality to simplify the models design process and give the hand the ability to be scaled to different sizes for different users. Based upon the 2015-2016 3-D Prosthetic Hand MQP, a few relations have been identified in the palm and fingers which will used in this project. The group had great success in defining and creating these relations. It could be an element that adds to the unique qualities of the group's product.

⁷⁵ HSR-2645CR Servo, n.d.

PALM			Fingers (3-Joint)		
Variable Name	Value/Equation	Comment	Variable	Equation	Comment
Length	$(3.5 * \text{extrusion}) / 4$		FingerWidth	$\text{FingerLength} / 7$	
Height	$(2 * \text{extrusion}) / 4$		FingerLength	$\text{length} * 2.4 - 3.5$	
Extrusion	$\text{inputhandwidth} / .75$		ProximalLength	$\text{FingerLength} / 2.2$	
L1	0.35	Pin cut length	DistalLength	$\text{FingerLength} / 4.1 - \text{EndOffset}$	
h1	0.2	Pin cut height	MiddleLength	$\text{FingerLength} / 3.3$	
inputhandwidth	2.8	Input width of hand	GapWidth	$\text{FingerWidth} / 2.2 + 2 * \text{EndOffset}$	
FingerLength	$\text{length} * 2.4 - 3.5$		EndOffset	0.4	
PinDiameter	0.2		Length2	$\text{length} / 2 + 1$	
ProximalLength	$\text{FingerLength} / 2.2$		Width2	$\text{height} / 3.2$	
DistalLength	$\text{FingerLength} / 4.1 - \text{EndOffset}$		ComponentLength	$\text{length} / 2$	
MiddleLength	$\text{FingerLength} / 3.3$		ComponentWidth	$\text{height} / 5.2$	
EndOffset	0.4		ThumbWidth	$\text{FingerWidth} * 1.4$	
TERMS			tthumbheight	$\text{thumbwidth} * .7$	
Distal	Tip		tthumblength	$\text{thumbwidth} * 1.5$	
Middle	Mid				
Proximal	Base				

Figure 55: Equations and relations table

The equations and relations have been broken into their locations, the palm and the three-joint fingers. The palm contains relations such as lengths and heights that define separate dimensions of the palm which are all dictated by the “inputhandwidth” relations which has a domino-effect on the other relations. The fingers contain similar, yet more uniquely attributed, equations all dictated by a similar “inputhandwidth” command that exists by relating to the palm’s relations. These relations are all reliant, as well as commanded by one another with an order of command that trickles through the data flow. With these being identified, the hand itself will have the powerful option of scaling for different users in terms of their personal physical measurement fittings. This way, users of all ages and varying physical attributes the opportunity to adopt the product.

Even with the relations from last year, the team must define their own relations to their model. Last year’s model was not altered to create the new product due to the difference in nature and goals of the projects. Beginning with a new model allows for the ability to adopt overarching relationships from last year and gives the group the opportunity to define their own relations.

6.5 Engineering Standards

With the development of a new product there has to be standards in place to make sure that it can be compared to other products and see if it can even be used commercially. The standards that are used currently are in the testing aspect of a prosthetic. The prosthetic must have all of its components undergo stress tests to see if they can support enough weight to serve as a prosthetic. In addition, the device must undergo cyclic testing to see how long it can function without breaking. For prosthetics in general the cyclic testing is very important and while there is no standard for prosthetic hands of this caliber currently using similar parameters would be acceptable. If further development of the prosthesis is done then recording the data from the cyclic and load tests in compliance with the standards listed below.

E467 - 08(2014)	Standard Practice for Verification of Constant Amplitude Dynamic Forces in an Axial Fatigue Testing System
E1942 - 98(2010)e1	Standard Guide for Evaluating Data Acquisition Systems Used in Cyclic Fatigue and Fracture Mechanics Testing
E2443 - 05(2010)e1	Standard Guide for Verifying Computer-Generated Test Results Through The Use Of Standard Data Sets

E647 - 15e1	Standard Test Method for Measurement of Fatigue Crack Growth Rates
E1457 - 15	Standard Test Method for Measurement of Creep Crack Growth Times in Metals
E1681 - 03(2013)	Standard Test Method for Determining Threshold Stress Intensity Factor for Environment-Assisted Cracking of Metallic Materials
E2760 - 16	Standard Test Method for Creep-Fatigue Crack Growth Testing

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Appendices

Appendix A: Nomenclature

Term	Definition
ABS	Acrylonitrile butadiene styrene , a plastic used in additive manufacturing.
ADL	Activity of Daily Living , routine activities that people tend to do every day without needing assistance. There are six basic ADLs: eating, bathing, dressing, toileting, walking, and continence.
CPU	Computer Fan . In most cases it is a Central Processing Unit but in this project it is used to denote a computer fan.
EMG	Electromyography , a diagnostic procedure to assess the health of muscles and the nerve cells that control them (motor neurons). Motor neurons transmit electrical signals that cause muscles to contract. An EMG translates these signals into graphs, sounds or numerical values that a specialist interprets.
MQP	Major Qualifying Project , a major-related project at Worcester Polytechnic Institute.
PLA	Poly lactide , a plastic used in additive manufacturing.

Appendix B: Complete Directional Terms in Human Anatomy

Term	Definition
Sagittal Plane	Passes vertically through the body. Divides the body into right and left sections
Median Plane	Sagittal plane that divides the body into two equal halves
Frontal Plane	Passes vertically through the body, but is perpendicular to the sagittal plane. Divides the body into anterior and posterior sections
Transverse Plane	Passes horizontally through the body. Divides the body into superior and inferior sections
Ventral	Toward the front or belly
Dorsal	Toward the back or spine
Anterior	Toward the ventral side
Posterior	Toward the dorsal side
Supine	Anterior face up
Prone	Posterior face down
Cephalic	Toward the head or superior end
Rostral	Toward the forehead or nose
Caudal	Toward the tail or inferior end
Superior	Above
Inferior	Below
Medial	Toward the sagittal or median plane

Lateral	Away from the sagittal or median plane
Proximal	Closer to the point of attachment or origin
Distal	Farther from the point of attachment or origin
Ipsilateral	On the same side of the body
Contralateral	On opposite sides of the body
Superficial	Closer to the body surface
Deep	Farther from the body surface

Appendix C: Activities of Daily Living

Appendix C.1: Detailed Descriptions of the Activities of Daily Living

Area	Description
Food preparation	Food preparation tasks: selecting ingredients, preparing them to be cooked (peeling, cutting, cleaning, etc.) and cooking them.
Feeding	Eating (and drinking) and other related tasks such as serving food on crockery and liquids in glasses.
Personal care	Tasks related to personal care and hygiene: getting dressed, brushing hair and teeth, making up, shaving, etc. Private care was excluded.
Housekeeping	Doing the laundry, hanging it out and ironing it, washing dishes, sweeping, cleaning, etc.
Shopping	Daily shopping tasks (food and cleaning): pushing the trolley, taking items and paying. Less frequent shopping like clothing and consumer goods was not included.
Driving and transport	Driving and maintaining the car and using public transport.
Leisure	Daily leisure activities at home like watching TV, reading, listening to music, playing cards or videogames. Sports are excluded.
Others	Talking on the phone, moving around the house, etc.

From Vergara, M. et al. *Journal of Hand Therapy* **27** (2014) 226

Appendix C.2: Hand Usage during Activities of Daily Living

Daily time (hours and minutes) per day spent in each area, adapted from ATUS, and estimated time per day that hands are used in each area of ADL

Area of daily activities	Daily time (ATUS)	Daily time of hand use
Food preparation	34'	30'
Feeding	1 h 15'	1 h 9'
Personal care	48'	46'
Housekeeping	34'	32'
Shopping	27'	19'
Driving and transport	49'	25'
Leisure ^a	3 h 37'	1 h 5'
Others	21'	20'
Total	8 h 25'	5 h 6'

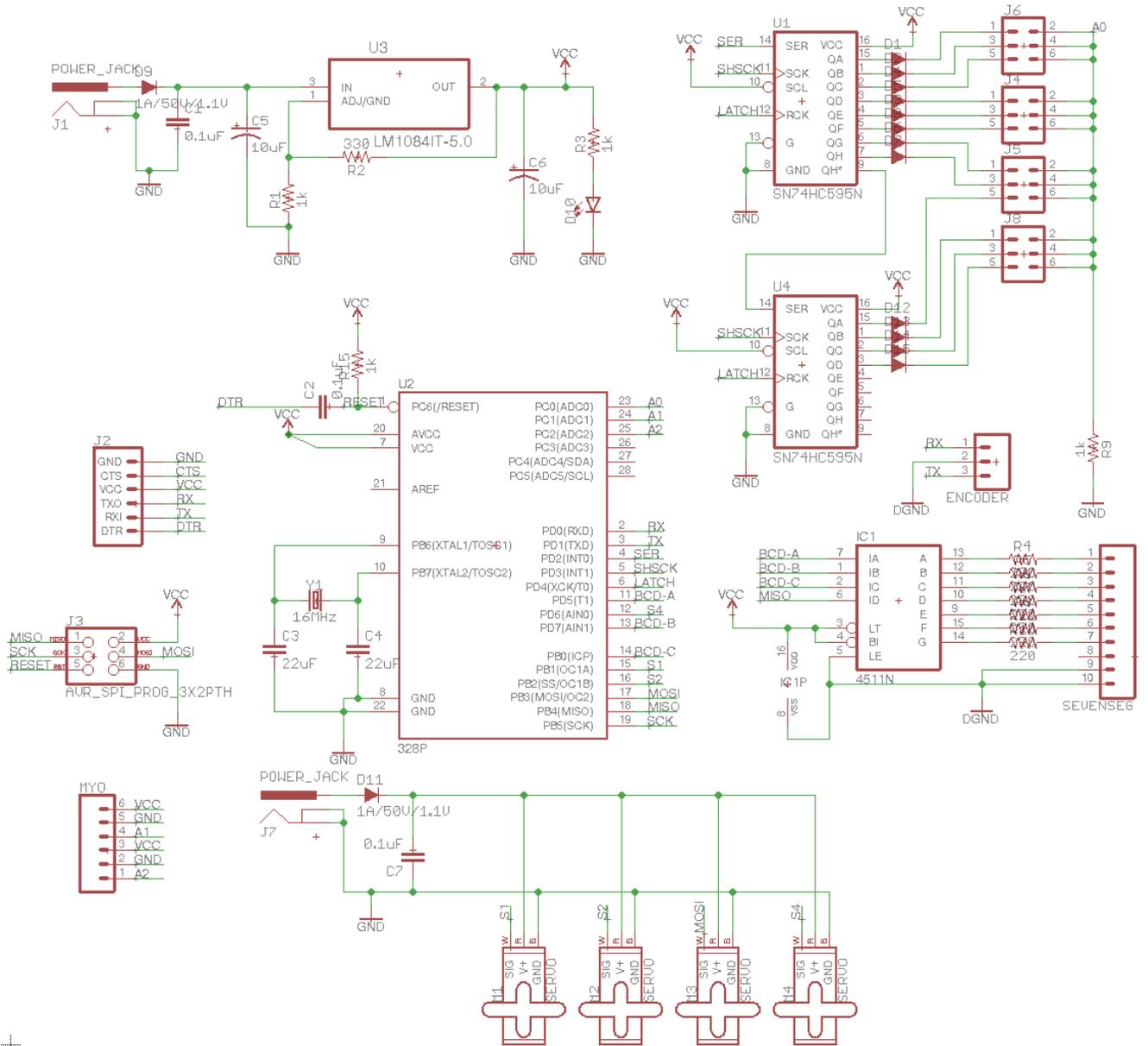
^a Time spent on sports is excluded.

From Vergara, M. et al. *Journal of Hand Therapy* **27** (2014) 228

Appendix D: Design Goals Decision Matrix

Design Goals	Weight	Max Capable Load	Range of Motion	Cost	Time to Assemble	Difficulty to Assemble	Durability	Environmental Factors	Time to Print	Scalability	Aesthetics	Safety	Serviceability	Comfort	Ease of Use
Weight	1	1	1	0	0	0.5	1	0	0	0	0	1	1	1	1
Max Capable Load	0	0	0	0	0	0	1	0	0	0	0	1	0.5	1	1
Range of Motion	0	0	0	0	0	0	1	0	0	0	0	1	0	0.5	1
Cost	1	1	1	0	0	0	1	0	0	0.5	0	1	1	1	1
Time to Assemble	1	1	1	1	0	1	1	1	0	1	1	1	1	1	1
Difficulty to Assemble	0.5	1	1	1	0	0	1	0	0	1	0.5	1	0.5	1	1
Durability	0	0	0	0	0	0	0	0	0	0	0	1	0	0.5	0.5
Environmental Factors	1	1	1	1	0	1	1	0	0	1	0	1	1	1	1
Time to Print	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1
Scalability	1	1	1	0.5	0	0	1	0	0	0	0	1	0.5	1	1
Aesthetics	1	1	1	1	0	0.5	1	1	0	1	0	1	1	1	1
Safety	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Serviceability	0	0.5	1	0	0	0.5	1	0	0	0.5	0	1	0	1	1
Comfort	0	0	0.5	0	0	0	0.5	0	0	0	0	1	0	0	1
Ease of Use	0	0	0	0	0	0	0.5	0	0	0	0	1	0	0	0
SUM	6.5	8.5	10.5	5.5	1	4.5	12	3	0	6	2.5	14	7.5	11	12.5
RANK	8	6	5	10	14	11	3	12	15	9	13	1	7	4	2

Appendix E: Schematic for Control System



Appendix F: Full Test Procedures

Appendix F.1: Pins Test Procedure

Background

The 3D Printed pins in the hand must support the weight of the objects the user desires to interact with. The pins are present at the base of the fingers, connected to the palm and connecting the fingers in the joints. Understanding how the pins will respond under different loads will determine if the pins are ready to be used in the final assembly as they are designed. Failure to hold the load, then a redesign will be necessary.

Abstract

Objective: The objective of this test is to determine whether the pins placed at the finger joints will be able to withstand a tensioning force, up to 10 lb. for a 100% passing rating. All testing will be done in a tensioning Instron machine. The classification of success and failure is described below.

Design: The pins will be rated on percentage of desired strength to experimental values. 0% will act as the low (failing) end of the scale while 100% acts as the highest (successful). The breakdown of the individual ratings is below. Weight (in pounds) supported will be characterized by 'X'.

The pins will be rating on that scale and further categorized into either a Failure or Success.

Failure

- A pin of a rating lower than 80%

Success

- A pin of a rating of 80% or higher

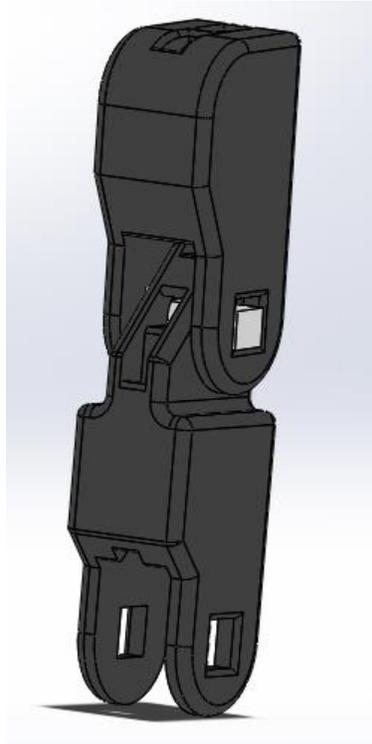
A success signifies that no further design is needed. A failure signifies that a redesign is needed. A video recording will be done of the test to review any failures or gap in the procedure that could lead to failure. This will be useful in reviewing why a failure might occur and what steps should be taken to rectify the issue or alteration in the design.

The experiment will be run with three different types of joint pins; horizontally printed, vertically printed, and pins printed with an alteration to the flex cut. With the data, the pin type that completes the experiment successfully or the highest rating will be pursued for the final design.

Experimental Procedure

Equipment List

1. Finger Assemblies, as shown in the image below



2. 3 assemblies
 - One with Pins printed horizontally
 - One with Pins printed vertically
 - One with Pins printed with alteration to the flex cut.
3. Instron Machine.
4. Data Collection software.
5. Extra pins and finger components in case of failures.
 - At least three whole Finger Assemblies

Experiment

A traditional approach to mass measurement is by utilizing a digital weighing scale.

1. The finger assembly will be placed the instron vices with the Finger Top in the upper vice and the bottom Finger Mid in the bottom vice.
2. The vices will be tightened to a level that grips, but does not damage the components.
3. The instron will pull the finger up to 10 lb., or fracture, whichever occurs first.
4. The experimenter will record the data in both the software and the data collection table

(Table 2).

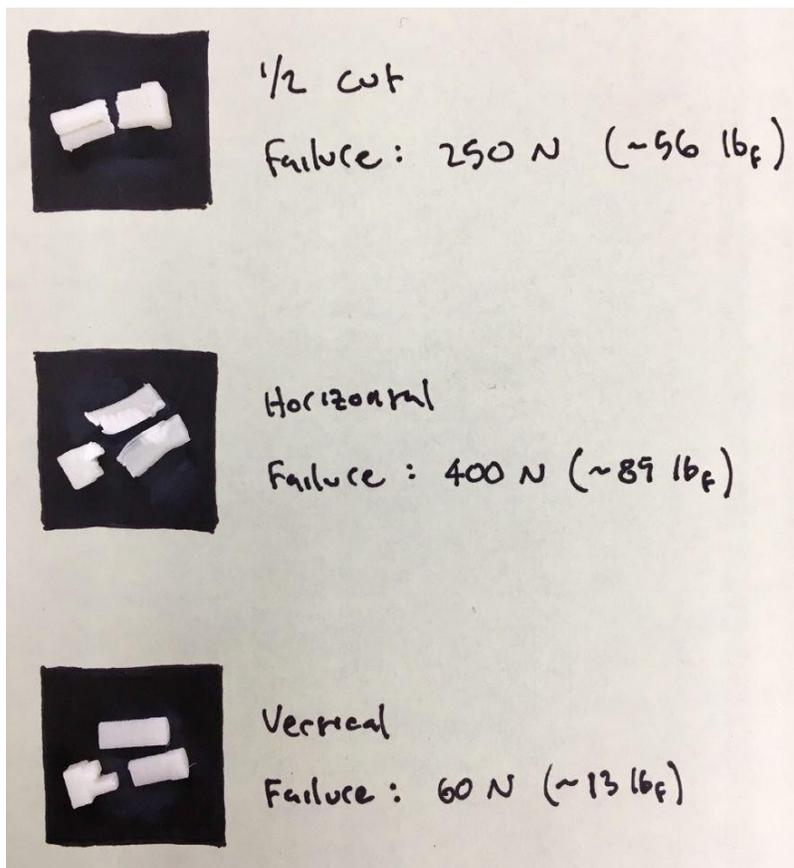
- The experiment will be repeated for the 3 assemblies outlined in point 1 of the Equipment List to determine which pin/finger assembly is strongest.

Table 2: Rating Calculation

Pin # (Type)	Total Load (N)	Total Load (lbf)	Rating (%)	Notes	Pass/Fail
Joint Pin 1 (1/2 Cut Design)	250	56.2	562	Fractured right in middle in part, image below.	Pass
Joint Pin 2 (Horizontal)	400	89.9	899	Fractured at the end of the cut, image below	Pass
Joint Pin 3 (Vertical)	60	13.5	135	Fractured at the edge of the cut, image below	Fail

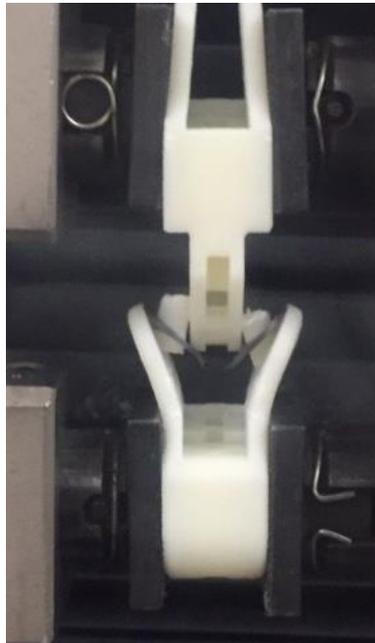
Results and Conclusions

All pins passed the test on a numerical level as they all exceeded 10 lb. by the time they catastrophically failed. However, Pin 3 (Vertical) began fracturing before the mark was reached, leading the experimenter to deem it as a failure. Below is an image of the results and the pins right after their testing.



From this image, the location, force, and manner in which the fracture occurred can be observed.

As the pins did exceed the expectations of the test, the test was deemed an overall success. The pin that will be used in the final model is Pin 2 (Horizontal). This pin performed the best of the three. The design was developed to be strong so the weakest point wouldn't be in the middle, where the weight would be concentrated. As the ½ Cut pin performed successfully as well, it did not perform the best because the weakest point, where the middle cut is placed, is where the weight was fully concentrated. Below is the image of how Pin 1 (½ Cut) fractured within the assembly. The other pins fractured in a similar manner.



The wings of the finger do appear to be damaged in this image. However, they only elastically deformed and returned to their original shape when released from the Instron. There was no other damage to the finger components.

There is no need for a re-design as the pins tested past the requirement of the prosthetic's application.

Error Analysis

There are sources of possible error. The Instron is not expected to be inaccurate, but calibration can always prove to be an issue. Under the supervision of a lab monitor, the experimenter will calibrate the machine per the machine's standard procedure. Another source of error is pin placement. If the pin is not seated properly in the assembly, the results could be inaccurate. Before being placed in the machine, the pin will be seated correctly by the experimenter. Once loaded into the machine, the experimenter will visually confirm the pin is still seated properly. If it is not, the assembly will be taken out and the pin will be resealed and the process will repeat.

Comments and Reflections

There is not too much to comment on as the pins performed as expected. It does stand out to how much weight the pins were able to support compared to what was needed of them. However, the strength is consistent with the tensile and shear strength of PLA and the characteristics of 3D Printing PLA. With these all considered, it is clear that the results are consistent with how the pins were designed and manufactured. There are no suggestions for how to improve the design as it passed the test.

Appendix F.2: Finger Actuation Test Procedure

Abstract

Background

Actuation of the fingers is essential to the functionality of the prosthetic design. Without proper function the hand can cause damage to property or even injury to the user. Inconsistency in ease of use will result in a poor product and ultimate abandonment by the user. Though not every prosthetic arm has the ability to actuate fingers, those that do must do so correctly or the benefits of a more expensive device are lost.

Objective

To determine if the design of the finger is able to complete the full motion required to complete desired activities.

Description

Each trial should be recorded to determine how long it takes the finger to complete a full closing and opening. The motion will also be recorded to determine if there is a smooth transition between fully opened and closed, and to determine if the joints function properly. The classification of Failure and Success are defined below.

Equipment List

1. 4 x Fully assembled fingers
2. 1 x Thumb
3. 1 x Palm
4. 10 x 6 inch lengths of thread
5. 4 x HS-5585mh servos
6. 1 x 5v power supply
7. 1 x Control Board
8. 1 x Arduino
9. 1 x 7.4V Battery
10. 1 x Servo housing
11. 10 x 8-32 ½ inch bolts
12. 10 x 8-32 nuts

Procedure

- Assemble the finger(s) to the hand using the provided pins
 - The fingers must be threaded to the servo such that the finger can be actuated properly (see assembly instructions)
- Attach the servo to the power supply

- Test the finger using the first, provided, prewritten program
- Ensure the finger completes one full cycle of opening and closing
 - The finger should start in the open position.
- The following data should be recorded:
 - Time required to complete one cycle
 - note: the time recorded should be when the signal for actuation is started to when the finger reaches its fully closed or open position
 - Pass or fail of each cycle
 - Time required to complete (50) cycles
 - Observations of any kind, especially the smoothness of the cycle(s)
- Test the finger using each of the next, provided, prewritten programs and record the requested data above.
- In order to measure continuous actuation success during testing, each actuation will be measured using a protractor to ensure the hand is closing properly and consistently at equal angles.

Failure

- Inability to close at all
- Inability to close fully within (5) seconds
 - Finger “closed” is defined as all three segments of fingers being used in the specific program curling inward at least 110 degrees around their respective pin joints.
- Inability to open at all
- Inability to open fully within (5) seconds
 - Finger “open” is defined as all three sections of all four fingers lying parallel to the bottom of the palm (angle between joints equal to or exceeding 160 degrees).
- Inability to follow the same motion for (50) cycles
- Dealignment of the finger/joints

Success

- Finger can close/open for all (50) cycles without failures
 - Examples of major failures include but are not limited to: pin separation, thread separation, thread breaking, finger breaking
- Finger “open” is defined as all three sections of all four fingers lying parallel to the bottom of the palm (angle between joints equal to or exceeding 160 degrees).
- Finger “closed” is defined as all three segments of fingers being used in the specific program curling inward at least 110 degrees around their respective pin joints.

Notice

- With continued use, wear of the thread and plastic components may affect the results of these findings negatively
- With continued use, particulates such as dirt, oil and water may affect the results of these findings negatively

- Failure of servo receiving or sending information for actuation does not mean the arm fails “Finger Test- Actuation”

Data Collection and Analysis

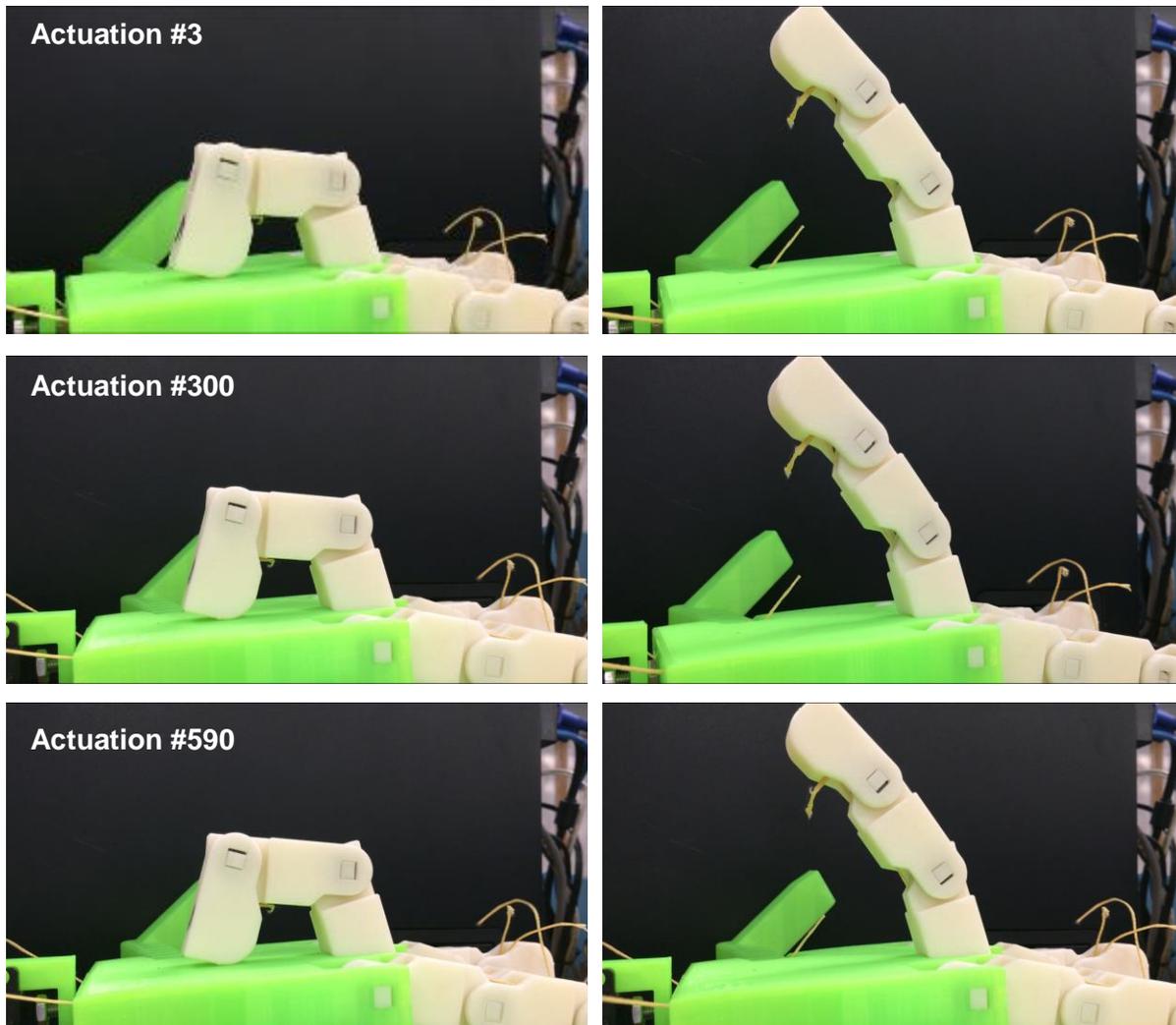
Table 1: Test Recording

Actuation #	Time to Actuate (seconds)	Angles of Close (Tip, Middle, Bottom)	Angles of Open (Tip, Middle, Bottom)	Time to Open	Success?/Notes
1	1.8	101 108 80	170 160 80		FAIL
2	1.8	101 108 80	170 160 80		FAIL
3	1.8	101 108 80	170 160 80		FAIL
4	1.8	101 108 80	170 160 80		FAIL
5	1.8	101 108 80	170 160 80		FAIL
6	1.8	101 108 80	170 160 80		FAIL
7	1.8	101 108 80	170 160 80		FAIL
8	1.8	101 108 80	170 160 80		FAIL
9	1.8	101 108 80	170 160 80		FAIL
10	1.8	101 108 80	170 160 80		FAIL
11	1.8	101 108 80	170 160 80		FAIL
12	1.8	101 108 80	170 160 80		FAIL
13	1.8	101 108 80	170 160 80		FAIL
14	1.8	101 108 80	170 160 80		FAIL
15	1.8	101 108 80	170 160 80		FAIL
16	1.8	101 108 80	170 160 80		FAIL
17	1.8	101 108 80	170 160 80		FAIL
18	1.8	101 108 80	170 160 80		FAIL
19	1.8	101 108 80	170 160 80		FAIL

Results and Reflections:

The result of this testing done on **February 24th 2017** was a **failure**, but the mechanism shows promise. In earlier design we had overlooked the fact that our servo motors, which have a range of 200 degrees, only have a programmable range of 110 degrees. This lack of motion illustrates why we were unable to obtain full actuation. We believe these results to be promising because of the repeatability of our actuations. This test was run simultaneously with the pin friction test and showed almost identical results over 600 actuations. Moving forward we have two options to have a successful test run. Our first option is to increase the radii of the cable tracks to compensate for the lack of arc length. Our second option is to purchase a servo programmer to unlock the remaining 90 degrees of motion our motors are capable of.

****Upon re-testing, the test was a success. However, the team has deemed this experiment a failure due to concerns users may not be able to repeat the results at this time.****



Appendix F.3: Thread Ductility Test Procedure

Abstract

Objective: The threads used in the prosthetic must be able to support different weights the prosthetic will be used to pick up on a daily basis. The threads run through each finger and are attached to servos in the wrist. When the servos rotate, the thread is pulled on and then the finger is closed. Not only is it important to understand whether the thread can be used to actuate the fingers, but also see if it can withstand holding weights as described in the user requirements. If the thread deforms more than is described in the failure section then a different thread will have to be used to actuate the fingers.

Design: To determine if the thread selected will deform while holding weights described in the user requirements. The user requirements state the prosthetic must be able to hold 10 pounds without elongating 3% to be considered for use. The amount of thread used in each finger is 12 inches. For the finger to actuate accurately the thread is cut to a precise length. If the thread elongates longer than 3% then it will cause errors in the program used to actuate the finger. The thread will have the weight attached and free hanging for 5 minutes. The classifications for success and failure are described as:

Failure

- Greater than 3% elongation
- Breakage of a load less than 10 lb.

Success

- Less than 3% elongation
- No breakage under a load less than 10 lb.

Background

The thread must meet the requirements of being able to support at least 10 pounds while showing minimal elongation. If the thread elongates past 3% when it is used to actuate the finger the change in length will make it less efficient in closing the fingers. If the thread is deemed a failure then it cannot be used for the prosthetic.

An intron will be used to test the thread. The weights that are being used will be different gallon jugs of water. The various jugs will have weights that are either 2, 3, 5, 8, & 10 pounds. Thread segments of six inches each will be tested. Each one of the jugs will be tied to the thread and then allowed to hang freely. After five minutes of hanging the jug will be untied and the next jug will be tested on a new length of thread.

Experimental Procedure

Experiment List

1. Thread segments.
2. Hanging masses
3. Ruler

Experiment

A traditional approach to mass measurement is by utilizing a digital weighing scale.

1. The thread will be placed in a vice with the one thread end in the upper vice and the other thread end in the bottom vice.
2. The vices will be tightened to a level that grips, but does not damage the thread
3. The hanging masses will be tied to the finger to first for 2lb, held for 60 seconds, released, inspected for damage.
4. If not damage, repeat for 3lb, and so on until 10lb or a failure takes place.
5. The experimenter will record the data during each weight equivalent.
6. The experiment will be repeated for a total of 3 assemblies to ensure repeatability.

The following table will be used to determine whether the thread is a success or a failure.

Weight Used (pounds)	Thread Failure? (Yes/No)	Elongation Percentage (%)	Success or Failure (< 3%)	Notes
2	No	0%	Success	The thread was able to hold the weight without any problems
3	No	0%	Success	The thread was able to hold the weight without any problems
5	No	1%	Success	The thread was measured to have elongated, but visibly remained the same
8	No	1%	Success	The thread was measured to have elongated and started to become unraveled.
10	No	2%	Success	The thread was able to hold the weight, but a constant problem that occurs is it unravelling after some time

The data will be gathered for at least three different trials. The notes section can be used to describe if there were any abnormalities with the test procedure. An example is if the thread came unraveled during the test, but did not break.

Results and Conclusions

The thread that was tested (Kevlar Thread) was able to support the desired weights while keeping within the elongation percentages allowed. The most the thread elongated was while using 10 pounds. The length of thread that was used was 12 inches and the longest that it was elongated was only .2 inches which is well within the range of passing. The Kevlar thread has been determined to be able to support common weights that a person would encounter on a day to day basis.

Error Analysis

There are possible places for errors to occur during the experiment. The accuracy of the equipment being used leave room for error as they could not be precise enough to capture the accurately determine at what weight the thread failed at. The thread length can also vary from segment to segment. Each will be cut to as accurately as possible, however, a change in the length can affect the results of the test. Each segment will be measured before each test to ensure that the segments are as close to each other as possible.

Comments and Reflections

The Kevlar thread did well under the various weights it was tested with. An area of concern, however, that has come up numerous times is with the thread unravelling. The thread is braided together with 3 different strands and when the thread is constantly tied and untied it quickly comes apart. The thread is still usable, but makes it difficult to string through the fingers or servo heads when they get frayed at the ends. There has not been another thread that we have currently found that would be able to yield the same results as the Kevlar thread so the thread will still be used. If there was another thread that was as strong as the Kevlar, but did not come easy unraveled that would be the ideal thread to use in the hand.

Appendix F.4: Socket Slippage Test Procedure

Abstract

Objective: The objective of this test is to measure the slippage of the prosthesis on the arm. To simulate normal loading and unloading during daily use, the prosthesis will be affixed to a model of a residual limb as if it were an actual amputee's arm and tightened securely. Hanging masses will be hung from the prosthesis for one minute. Multiple angles will be tested. The starting and ending positions of the prosthesis will be marked and measured. A Likert Scale will be used to rank the level of success or failure after the five minutes have passed.

Design: To test the slippage of the socket, the socket will be attached to the model of the residual limb at one of three test angles: 0 degrees (horizontal), 45 degrees, and 90 degrees (vertical). Hanging masses in the form of 2.5 lb. weights are to be hung from the fingers. Marked slip distance after one minute of testing will be measured with calipers that have been calibrated properly.

To test slippage on human skin, the socket portion of the prosthesis with the base plate removed can be worn on an actual human arm. The same test masses can be hung and the test can be repeated.

Table 1: Likert Scale for Ranking

Rank	Slip Distance
7	< 0.5 cm
6	0.6 - 1.0 cm
5	1.1 - 1.5 cm
4	1.6 - 2.0 cm
3	2.1 - 2.5 cm
2	2.6 - 3.0 cm
1	> 3.0 cm

Failure

- Under any of the test mass loadings, a rating less than 5.

Success

- Under any of the test mass loadings, a rating greater than 5.

A success signifies that the current design is sufficient and no further design modifications are needed. A failure signifies that a redesign is needed. A video recording will be made of the test to review any failures or gaps in the procedure that could lead to failure. This will be useful in

reviewing why a failure might occur and what steps should be taken to rectify the issue or alteration in the design.

Background

Due to the nature of human skin expanding and contracting with changes in internal and external temperature, the prosthesis will inevitably shift on the user's arm. It will also slip during general daily use due to natural loading and unloading, sweating, and the motion of the arm. This slippage should be limited as much as possible to ensure a fit that is both tight and comfortable. The largest issue associated with slippage is that if the prosthesis slips too severely it runs the risk of falling off, however slippage can also cause excess irritation to the user. A Likert scale, shown below, is used to rate the test results.

Experimental Procedure

Equipment List

1. Entire Hand Assembly
2. 2.5 lb. weights
3. Hooked bungee cords
4. Calipers

Experiment

Before the procedure is started, four one-gallon jugs of water will be filled to 2.5, 5, 7.5, and 10 pounds of water to serve as hanging masses.

Procedure

- Attach the prosthesis to a model of a residual limb using the socket and securing straps
- Align the model to a test angle
 - Test angles will be 0 degrees (vertical), 45 degrees, and 90 degrees (horizontal)
- Hang a test mass on the prosthesis
 - Test masses will be 2.5, 5, 7.5, and 10 lb.
- Mark the "zero" position, where the prosthesis started before timing
- Leave the mass hanging for 5 minutes
- Measure the amount of slippage
- Repeat for two trials of each mass per test angle
- The following data will be recorded:
 - Test angle
 - Test mass
 - Slip distance

Results and Conclusions

Test Angle: 0	Slippage Distance (mm)				
Trial	2.5 lb.	5.0 lb.	7.5 lb.	10.0 lb.	Rank
1: Joe	0 mm	2 mm	3 mm	4 mm	7
2: Rae	1 mm	2.5 mm	5 mm	12 mm	6
3: Cameron	2 mm	3 mm	4 mm	5 mm	7
Test Angle: 45	Slippage Distance (mm)				
Trial	2.5 lb.	5.0 lb.	7.5 lb.	10.0 lb.	Rank
1	0 mm	2 mm	3 mm	3.5 mm	7
2	0 mm	2.5 mm	4 mm	7.5 mm	6
3	1 mm	2 mm	2.5 mm	3.5 mm	7
Test Angle: 90	Slippage Distance (mm)				
Trial	2.5 lb.	5.0 lb.	7.5 lb.	10.0 lb.	Rank
1	0 mm	0 mm	0 mm	0 mm	7
2	1 mm	3 mm	5 mm	6 mm	6
3	0 mm	0 mm	1 mm	1 mm	7

As shown in the tables, the prosthesis ranked between 6-7, meaning the test passed. In general there seemed to be minimal motion in the prosthesis, with a lot of emphasis on shoulder strength rather than arm strength when resisting the weights. This test should be run again with the whole assembly, rather than just the socket, if at all possible.

Comments and Reflections

- After the weight is released, the socket returns to its original position
- Minor discomfort noted when holding 10 lb.
- Feels like it is the edges are pinching the arm on the back of the forearm

- Emphasis on shoulder muscle strength
- Sock stretching more than motion of the socket

Error Analysis

The weight distribution should be more accurately regulated; the way the weights were hung, they tended to move more towards the back.

Appendix F.5 Control System Hardware Test Procedure

Abstract

Objective: The objective of this test is to assess the functionality and efficiency of the hardware portion of the hand control system which is used in hand actuation, force sensing for actuation feedback, grip selection input and user display, and myoelectric flex sensing. Each connection on the board will be compared to the final schematic designs for the system and a multimeter will be used to ensure the appropriate voltages and currents are present throughout the system. Success of the hardware control system is contingent on a pass from the software control system test.

Design: The test is designed such that each part of the control system is compared to its respective design diagram and checked for accuracy. It can be assumed that if all parts of this tests pass but the hand functionality test fails then the problem lies in the initial circuit design.

Background

The control system for the hand was implemented using various pieces of electronic hardware in order to more efficiently control various aspect of the hand's functionality. The hardware was assembled by hand in a lab and thus must be tested to ensure all parts of the system are operating as expected. Also inherent in electrical systems are the possibilities for inefficient power usage and excessive heat output. The servos controlling the fingers' motion will be tested as well as the battery supplying power to the servos. Using various lab materials, the hardware for the control system will be thoroughly examined and tested for full functionality.

Appendix E is a schematic for the entire system and is an integral part of ensuring the validity of the assembled hardware. The schematic specifies the exact route of voltage between various parts of the system and thus should be understood fully in order to perform the experimental procedure in the next section.

The following is an outline of each component of the hardware and the expected state for each component to constitute a viable and working system:

Myoelectric Sensors

- All connections match schematic, are secure, and are electrically isolated from all other components
- Signal from sensor remains relatively static (± 5 units) when electrodes are in position and arm is at rest

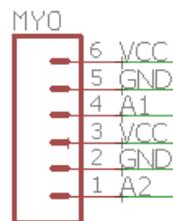


Figure 1 Myoelectric Sensor Schematic Symbol

Force Sensors Array

- All connections match schematic, are secure, and are electrically isolated from all other components
- 6-pin female connector is secure and connection is being made to all 6-pin wires of ribbon cable
- An oscilloscope will be used to measure the appropriate time interval necessary for probing each force sensor, frequency must be greater than 100Hz
- Outputs from force sensors remain relatively static when no force is applied (± 5 units)

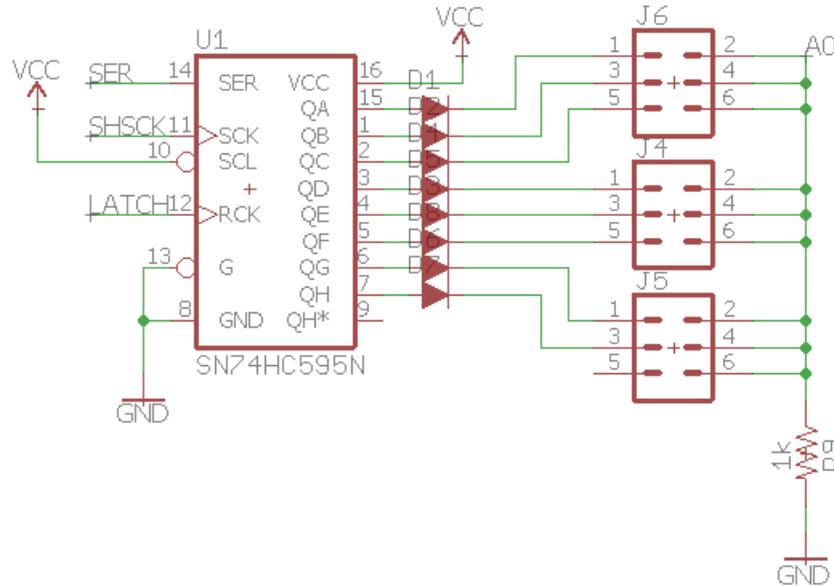


Figure 2 Force Sensor Array Schematic Symbol

Rotary Encoder Input

- All connections match schematic, are secure, and are electrically isolated from all other components
- Output from rotary pins matches expected output from datasheet

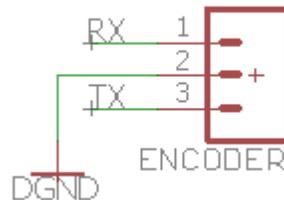


Figure 3 Rotary Encoder Schematic Symbol

BCD to Seven Segment Decoder & Display

- All connections match schematic, are secure, and are electrically isolated from all other components
- Output from pins match datasheet for each possible input signal
 - Appropriate number is displayed on screen, relative to input

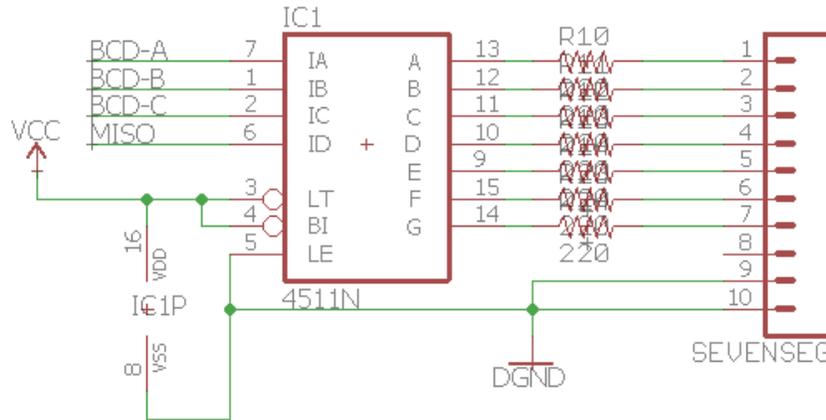


Figure 4 Decoder and Display Schematic Symbol

Servo Power and Data Headers

- All connections match schematic, are secure, and are electrically isolated from all other components
- Data input signal when no signal is applied rests within a specified voltage range ($\pm .25V$) and thus is unaffected by noise
- Servos are able to be controlled to any specific degree of rotation (118.5°) with specified speed ($079^\circ/\mu\text{sec}$)

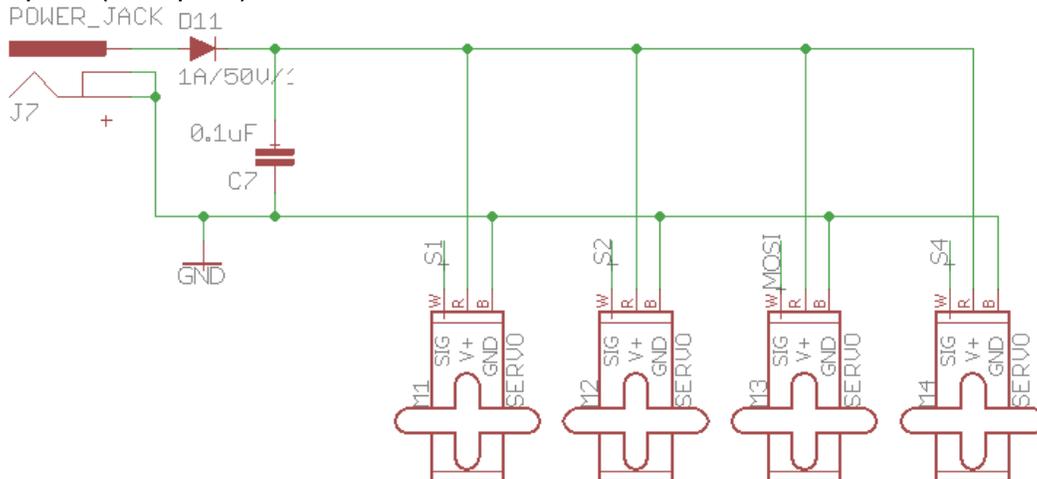


Figure 5 Servo Power and Data Schematic Symbol

7.4 LiPo 2C Battery

- All connections match schematic, are secure, and are electrically isolated from all other components
- Battery supplies specified voltage for appropriate period of time (2200mAh)
- With maximum load applied to battery, current is still supplied at the appropriate voltage rating ($7.4V \pm 1V$)
- No schematic symbol

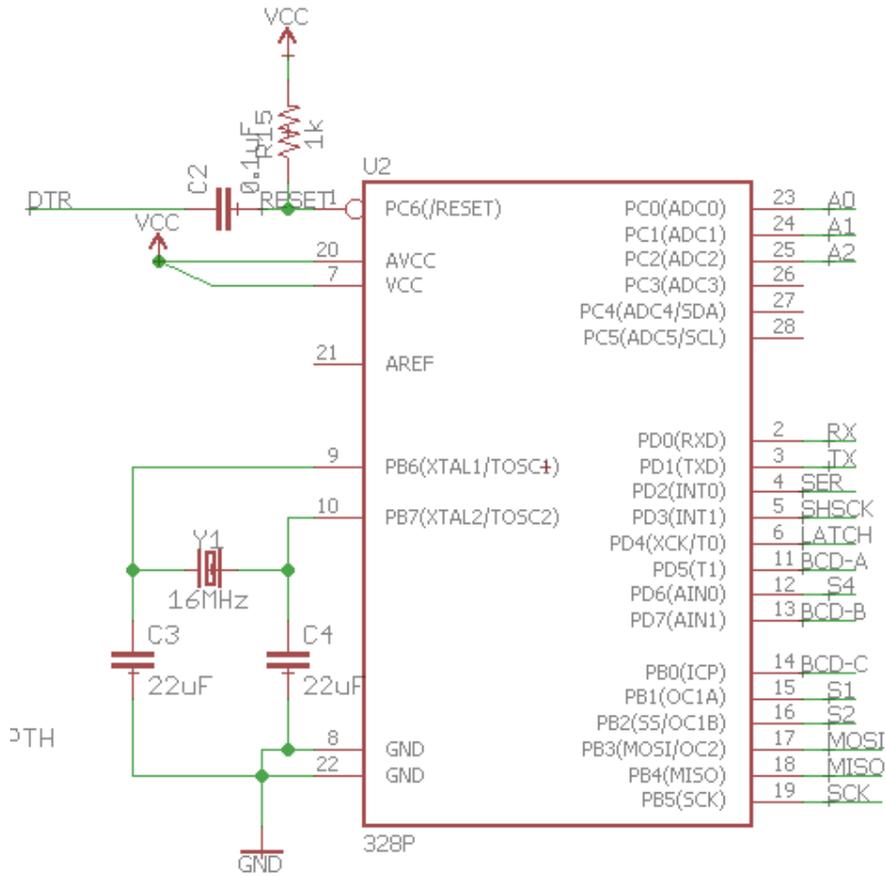


Figure 7 ATmega328P Schematic Symbol

Experimental Procedure

Equipment List

1. Entire Control System Assembly
2. Assembly Schematic
3. Power Supply capable of 9V @ 3A
4. Multi-Meter (V, A, Ohms) w/ Probes
5. Oscilloscope with four probes
6. Computer running Arduino IDE

Experiment

Procedure for Ensuring System Matches Schematic

- Isolate respective section of schematic diagram
- Choose wire on diagram and determine all connections to wire
 - o Wires with node may have more than two connections
- Use multi-meter to ensure current flow between each possible connection through specified wire
- Repeat for all wires in section

General Procedure

- Myoelectric Sensor:
 - Ensure connections match schematic
 - Connect myoelectric sensors to Arduino
 - Apply resistive pads to appropriate locations on skin
 - Connect sensor to pads
 - Use oscilloscope to look at data signal with no flex
 - Measure variation in signal and compare to expected signal as per the datasheet
- Force Sensor Array:
 - Ensure connections match schematic
 - Connect force sensors to 6-pin male connector
 - Use multimeter on resistance setting across male to female connection
 - Infinite reading means failure
 - General resistivity of wire means success
 - Attach oscilloscope lead to each pin of shift register and measure timing of signal
 - Calculate frequency of complete measurement cycle
 - Compare calculated frequency to expected frequency (100Hz)
 - Attach oscilloscope lead to analog output pin
 - Measure variation in signal and compare to expected signal variation ($\pm 0.25V$)
- Rotary Encoder Input
 - Ensure connections match schematic
 - Attach oscilloscope lead to each output pin of encoder
 - Verify that output matches appropriate value as outlined in datasheet
- BCD to Seven Segment Decoder & Display
 - Ensure connections match schematic
 - Attach oscilloscope to each output of decoder
 - Verify that output matches appropriate value as outlined in datasheet
 - Use multimeter to probe between display and output of decoder
 - Determine if all pins are effectively connected
- Servo Power and Data Headers
 - Ensure connections match schematic
 - Attach oscilloscope to each data input
 - Measure variation in signal and compare to expected signal variation ($\pm 0.25V$)
 - Use Arduino software to load a sweep program on Arduino
 - Attach each servo separately to power
 - Verify that 200 degrees of rotation is achieved
- 7.4 LiPo 2C Battery
 - Ensure connections match schematic
 - Use multimeter to measure voltage across battery
 - Connect one servo to battery
 - Use sweep servo program to continuously run servo
 - Measure current and voltage
 - Compare values to specification
 - Connect four servos to battery
 - Use sweep servo program to run all servos continuously
 - Verify that battery output remains sufficient
- DC to DC Converter (Hardware Iteration #2)
 - Ensure connections match schematic
 - Use multimeter to measure input voltage and current
 - Use multimeter to measure output voltage and current

- Apply max load to converter
 - Force sensors are being polled
 - Myoelectric sensors are being polled
 - Grip Selection is active
 - Servos are active
- Ensure output remains constant and unchanging ($\pm 0.25V$)
- ATmega328P Power and External Clock (Hardware Iteration #2)
 - Ensure connections match schematic
 - Determine clock speed of Arduino using oscilloscope

Resources Necessary for Testing

Myoelectric Sensor:

- Datasheet
 - o <https://cdn.sparkfun.com/datasheets/Sensors/Biometric/MyowareUserManualAT-04-001.pdf>

<https://cdn.sparkfun.com/datasheets/Sensors/Biometric/MyowareUserManualAT-04-001.pdf>

74HC595 Shift Register:

- Datasheet
 - o <https://www.sparkfun.com/datasheets/IC/SN74HC595.pdf>

<https://www.sparkfun.com/datasheets/IC/SN74HC595.pdf>

Rotary Encoder:

- Datasheet
 - o <https://www.sparkfun.com/datasheets/Components/TW-700198.pdf>

<https://www.sparkfun.com/datasheets/Components/TW-700198.pdf>

CD4511B Decoder:

- Datasheet
 - o <http://www.ti.com/lit/ds/symlink/cd4511b.pdf>

<http://www.ti.com/lit/ds/symlink/cd4511b.pdf>

HS-5585MH Servo:

- Specification
 - o <https://www.servocity.com/hs-5585mh-servo>

<https://www.servocity.com/hs-5585mh-servo>

Results and Conclusions

Portion of Test	Schematic Match?	Measurement	Notes	Result

Myoelectric Sensor	Yes	Min: 575mV Max: 730mV	Signal Wire Variation	No specified noise ratio in datasheet; able to differentiate flexed from relaxed PASS
Force Sensor Array	No (See notes)		QD(pin 3) inf resistivity QG(pin 6) inf resistivity	2 force sensors unable to send data FAIL
		Shift register frequency: 100Hz		Matches 100Hz frequency PASS
		Min: -30mV Max: 50mV	Refers to variation in analog signal	<.25V noise difference PASS
Rotary Encoder Input	Yes	1101, 0100, 0010, 1011 - > clockwise 1110, 0111, 0001, 1000 - > counter-clockwise	Used software to determine pin values Check datasheet	Recorded bit values match datasheet PASS
BCD to Seven Segment Decoder & Display	Yes	Output matches datasheet		Decoder output matches datasheet PASS
				Correct number seen on display PASS
Servo Power and Data Headers	Yes	min, max for each servo: -28mV, 56mV; -28mV, 56mV, -28mV, 56mV; -28mV, 56mV		<.25V noise difference PASS

		writeMicroseconds: 750 to 2245 -> ~160 degrees rotation		able to move minimum required distance and speed PASS
7.4 LiPo 2C Battery		7.62V,	One servo	After running sweep program, sufficient power output for one servo PASS
		7.58V	Four servos	After running sweep program, sufficient power output for four servos PASS
DC to DC Converter (Arduino Power Management)	second iteration; unable to test			
ATMega328P Power and External Clock	second iteration; unable to test			

Error Analysis

The only failure was infinite resistivity in pins 3 and 6 of the force sensor array, which signifies that the connection between the shift register and the pin is broken. This results in the respective force sensor for each not being able to be read by the microcontroller. The solution for this is to check the connection of each pin and rewire and/or re-solder each as necessary.

Conclusion

The tests were overall successful. All results of the tests were within or surpassed the specifications. The only issue experienced was two of the force sensor pins were disconnected with the shift register. The ATMega328P Power and External Clock was unable to be tested as that is a component of a custom PCB board that, while designed, is not physically created as of the time of writing. This also applies to the DC to DC Converter. Once the second iteration of board is created, these aspects will be tested.

Appendix F.6 Hand Functionality Test Procedure

Abstract

Objective: The objective of this test is to assess the functionality of the prosthesis' pre-programmed grips and gestures. These are: Open Hand, Closed Hand, Point, and Pinch. To do this, a scale of 1-7 is used to determine how well the prosthesis accomplished an assigned task, with 7 being success and 1 being failure.

Design: For this test, the prosthesis should be either secured to a test subject's arm (note: the base plate should be removed if the subject does not have a residual limb), or to a model of a residual limb. Once secure, the prosthesis will be tested using the procedures and objects outlined below. Each grip/gesture is to be tested with different objects as appropriate.

Failure

- Inability to complete the assigned task.

Success

- Ability to complete the assigned task.

A success signifies that the current design is sufficient and no further design modifications are needed. A failure signifies that a redesign is needed. A video recording will be made of the test to review any failures or gaps in the procedure that could lead to failure. This will be useful in reviewing why a failure might occur and what steps should be taken to rectify the issue or alteration in the design. Each grip will either succeed or fail.

Background

The prosthesis needs to be able to function as a system, not just as individual components. To this end, this test aims to assess how well the prosthesis can accomplish given tasks. This serves as an adequate measure of how functional the system is.

Experimental Procedure

Equipment List

1. Entire Hand Assembly
2. 7.4V Power Supply
3. Key
4. Tennis ball
5. Gallon jug
6. Soda Can
7. Door knob

Experiment

Each grip will have its own specific test and procedure to follow. The grips to be tested are: Open Hand, Closed Hand, Point, and Pinch. Each grip will be tested twice.

Initial Setup

- Assemble the prosthesis with the appropriate force sensors and electronics in place
 - o Force sensors should be placed in 12 locations on the hand and fingers
 - o Kevlar thread should be strung through the fingers and palm using the appropriate thread channels and holes, and attached to the servos located in the forearm

- Test the hand to determine if the fingers can move using the muscle sensors
 - Force sensors should be able to identify when they are in contact with an object
 - Muscle sensors should be placed on the arm in their appropriate, predetermined locations
 - The forearm's flexor and extensor muscles are used to open and close the fingers, respectively
 - Each finger should be tested individually as necessary
- Test the control system by adjusting the knob
 - observe whether or not each grip/gesture can be properly selected and executed

Open Hand Test

- All grips should default to open hand initially
 - Ensure that each grip/gesture toggles appropriately between the gesture and all fingers open by flexing and extending

Closed Hand Test

- Flex, with no object blocking the fingers. Ensure the hand can close into a fist, and then reopen
- Test the ability of the fingers to close around objects of various shapes and sizes
 - Specifically test: Doorknob, gallon jug handle, soda can, tennis ball
 - Each of these objects offers a unique shape that the fingers should be able to close around.
- Record results and observations

Point Test

- Ensure that the index finger does not actuate during the opening and closing of the hand into this gesture

Pinch Test

- Ensure the ring and little fingers do not interfere with the closing of the thumb, index, and middle fingers into the pinch grip.
 - These fingers should close first, followed by the pinching fingers
- Determine if the pinching fingers can adequately grip a key
 - Test if the key can be inserted into a lock, record observations

Comments and Reflections

Results and Conclusions

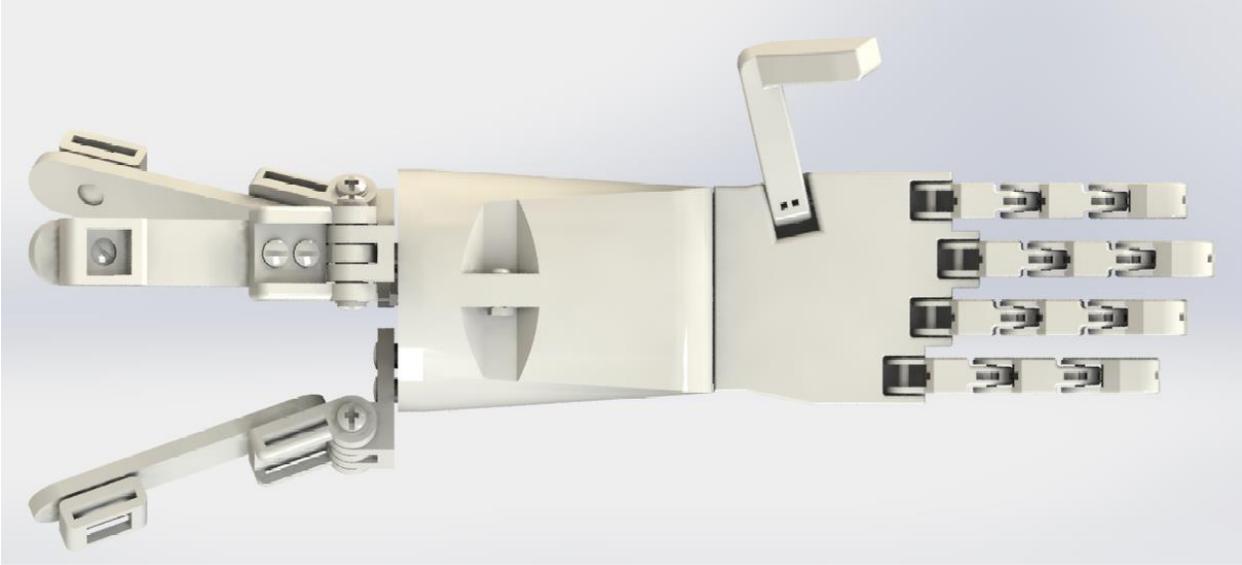
This test has been deemed a failure due to the actuations test failure. The experimenters believe the test would succeed but are not entirely confident that other experimenters and users can reliably repeat a successful actuation test, rendering functionality a failure.

Error Analysis

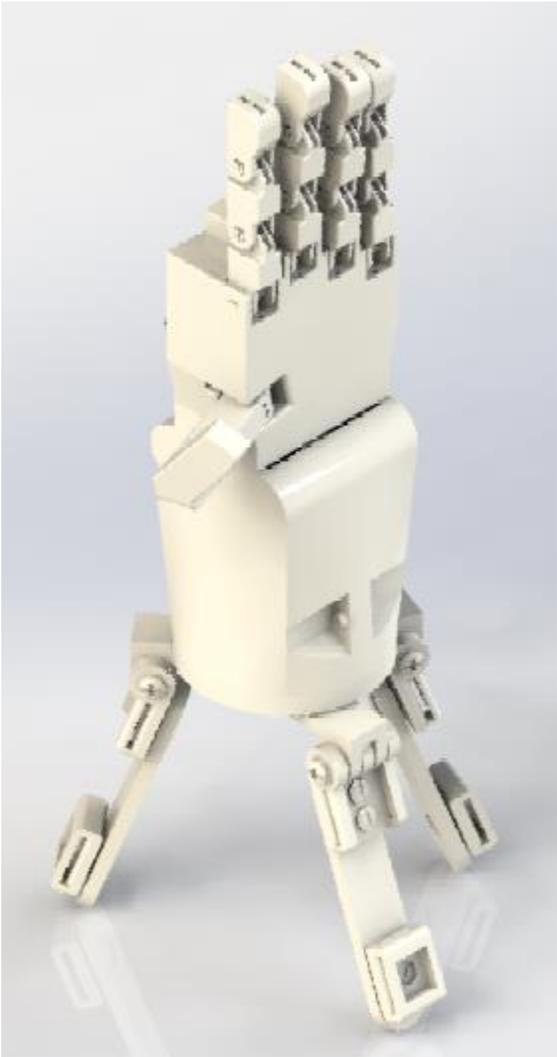
To compensate for possible error in either the 3D printed components of the hand or the driving control system, each grip or gesture will be tested twice. However, there is still the possibility of inconsistency due to noise, position of the object the hand is gripping, friction in the hand, or changes in the object. This inconsistency will be controlled and limited as much as possible.

Appendix G: Model Prototype Images

Appendix G.1 Bottom View



Appendix G.2 Isometric View



Appendix G.3 Manufactured Design

