Final Design Review
Electromechanical
3D Printed Prosthetic Arm Initiative

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KSU 2:
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Executive Summary

For this project, the task was to design a prosthetic arm for Kansas State University (KSU) that met several requirements concerning affordability, accessibility, and functionality. The preliminary steps were to research existing designs and analyze previous designs that KSU researchers had developed. The strengths and weaknesses of these designs were assessed and considered during the design phase of the first prototype. Previous models lacked mobility, as they did not have a full range of motion in the wrist. The ease of assembly was a challenge with these models, as well as scalability. Moving forward with the design process, the arm was broken up into components which each team focused on individually. Several different designs were considered and tested, specifically when it came to the actuation of the hand. The main issue was achieving an efficient mechanism to fully actuate all of the fingers at once. Additionally, the fingers and joints went through several modifications to optimize their performance in conjunction with the servo motors. The wrist also went through various revisions to resolve tolerance issues due to the wide range of rotation. Lastly, a priority was to make the entire design easily 3D printable with the simplest assembly process possible.

The prototype is controllable with an interface using the Dabble application through a bluetooth module that is connected to an Arduino Mega, and is powered by two 7.4V LiPo batteries. The controller has two different modes for full control of the prototype; one mode is used to control the actuation of the fingers and autonomous motion for an egg and cue ball. The other mode is utilized to rotate the wrist, bend the wrist up and downwards, and to actuate the elbow servo up and downwards. Four servos actuate the fingers and thumb to allow the user to pick up objects. The fingers flex back to an aligned state using 180° torsion springs, and are curled using spider wire which is tied to the fingertips and is pulled inward by the servos with the assistance of a 3D printed spool. The finger tips utilize TPU caps to provide higher friction which grants improved grip. The palm also contains a pressure sensor pad in the center to prevent the servos from over torquing and damaging objects. This pressure sensor is covered with a TPU cover in order to transfer the force to the pad while protecting it from foreign objects or conditions, while maintaining accurate readings. Finally, the prototype is scalable in the hand, fingers, and forearm by utilizing design tables in SOLIDWORKS, but has limitations due to the size of the components that were used. If smaller scales are desired, smaller components would be necessary, and the design tables would still be used. Recommendations for improvement consist of a higher torque servo for the elbow, reducing electronics within the forearm to a custom PCB for more space and organization, enhanced ease of assembly pertaining to the electronics and the wrist, and improved aesthetics.

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Background

Need

The World Health Organizations estimates that more than 30 million people are in need of a prosthetic limb [1]. However, the average cost of a prosthetic arm is approximately $20,000 - $80,000 [2]. Additionally, many of the components of these expensive prosthetic arms are proprietary, making repairs difficult as only the manufacturing company that sells the arm is capable of repairing broken pieces. As such, there is ample need to research and develop a cheap, reliable, and easily repairable alternative that is available to anyone that may require one.

Other Solutions

Currently, some popular prosthetic arms on the market are the Ability Hand from Pysonic, Adam's Hand from BIONIT LABS, and the Hero Arm from Open Bionics. Each design is quite similar, but relinquishes certain functions in favor of other chosen movements.

The Ability Hand ranges from $20,000-$30,000 and is marketed as being lightweight, durable, and waterproof with a large range of motion for the fingers, but lacks any form of articulate wrist movement [3]. More specifically, the Ability Hand is able to flex and extend every finger independently with the thumb being moved both electronically and manually. Additionally, the arm is bluetooth capable, allowing any mobile device to manipulate the arm for adjustments and provides an easy means for software updates. Lastly, the prosthetic has easy and fast charging, being able to go from empty battery to fully charged in just an hour.

The Adam's Hand starts at a base price of $30,000 and is marketed as having an adaptive grip pattern that can dynamically detect the strength needed to grasp objects [4]. Additionally, the prosthetic is made of aviation-grade aluminum joints with the hand and fingers composed of impact-resistant tecno-polymers and is waterproof with a quick disconnect at the wrist that allows for easy maintenance and repair. However, like the Ability Hand, it lacks any wrist articulation.

The Hero Arm ranges from $10,000-$20,000 and is marketed as being lightweight, powerful, and durable [5]. In particular, the arm is 340g and able to lift up to 8 kg. Additionally, Open Bionics advertises that the arm is highly customizable with many magnetic facades that snap onto the exterior of the prosthetic. However, just like the previously mentioned prosthetic arms, the Hero Arm lacks wrist mobility as the fingers are able to articulate and cover much of the required range of motion that a wrist could.

Initial Status

Kansas State University (KSU) is currently in possession of two prototype prosthetic arms. One was modified from downloadable 3D print files created by Tanmay Benjwal, who posted their parts on Instructables.com, and the other from an undergraduate research student, Billy Imig, at KSU who has been working on a version of the prosthetic arm (see Figures 1 and 2 respectively). However, the design is very rudimentary, lacking much of the desired mobility of a potential final product, such as wrist articulation and implementation of a microcontroller to move electronics. As such, the student's model will be used as reference, but new models will be generated and utilized for further studies.

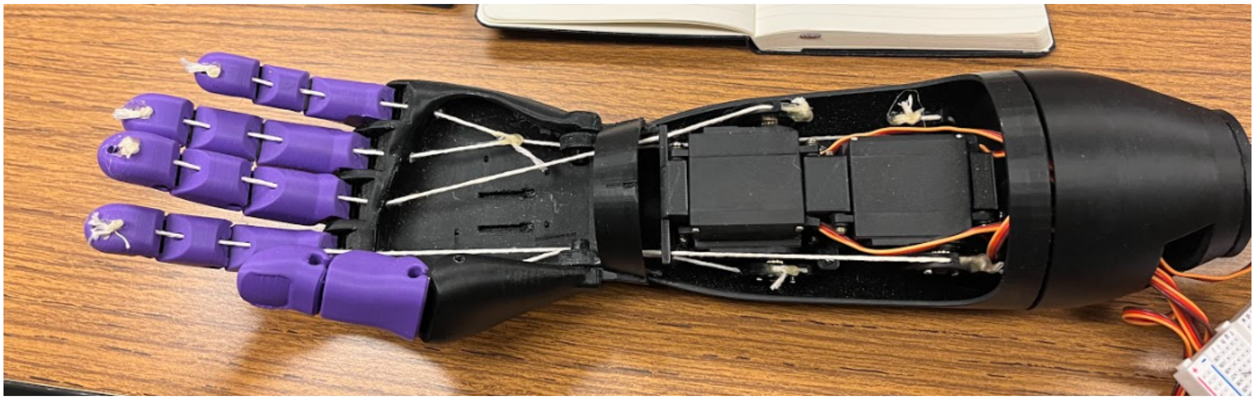

Figure 1. Initial Arm Design that was Downloaded and Modified from an Online STL Repository

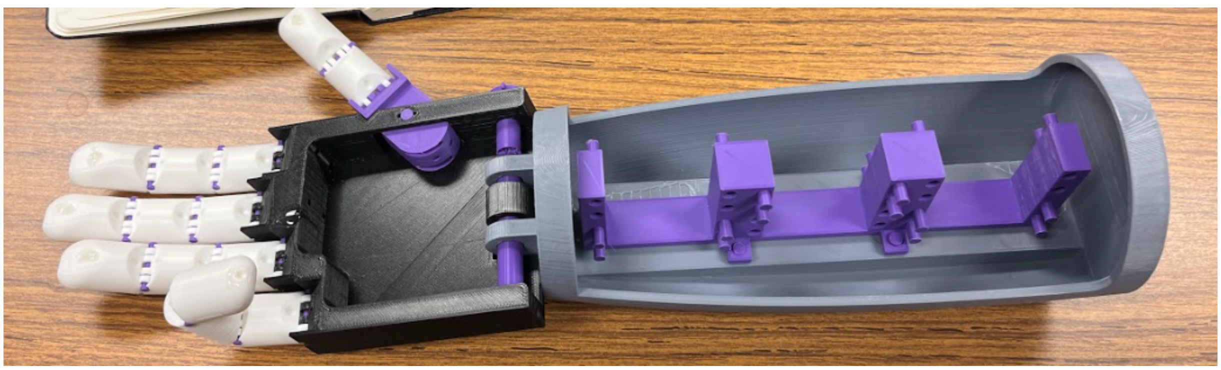

Figure 2. Undergraduate Researcher's Initial Design

Project Statement, Deliverables, Specifications

Project Statement

The project is targeted towards individuals with limited resources and financial means to purchase a prosthetic appendage. This project involves creating a 3D-printable prosthetic arm, including the forearm, wrist, hand, and fingers. The wrist has two axes of rotation and all fingers close towards the palm for gripping. The arm is intended to be constructable by any user, regardless of technical expertise. All parts are scalable to give the user three different options of hand and arm sizes. The palm has pressure feedback that can be programmed to ensure it will not crush or drop the objects the user is attempting to grip. Once completed, the created models, all purchased components, and all documentation will be uploaded to GitHub, an open source repository available to any individual who may want to view or create the product.

Deliverables

1. A complete model of the fingers, hand, and forearm in SOLIDWORKS.
2. A complete set of STL files for printing the fingers, hand, and forearm.
3. An assembled prototype of the hand and arm.
4. A supporting controller that allows the wrist to be rotated and the hand to be opened and closed.
5. Implementation of a feedback mechanism that allows the hand to grip both an egg without crushing it and a cue ball without dropping it.
6. Documentation for future development.

Specifications

1. The dimensions of the hand and arm must match that of Dr. Ronald Brockhoff (RCB).
2. The completed model must be scalable to different sizes.
3. All components must be printable or purchasable from mass distribution centers (i.e. Amazon, McMaster Carr, Digikey, etc.).
4. Upon completion, all files must be uploaded to GitHub as a public repository.

Detailed Documentation

Discussion of Deliverables

Because the research and development of the prosthetic arm will span over several years, all research and design work must be thoroughly documented. This includes the SOLIDWORKS and STL files to ensure that any attempts at replication or modification can be done seamlessly without the need for restarting. Additionally, the prosthetic arm must be capable of recognizing inputs by grasping an egg and cue ball during a demonstration of the prototype.

Discussion of Specifications and Justifications

Moreover, to ensure replicability, all aspects of the prosthetic hand and arm must mimic RCB's dimensions (see Appendix A for RCB hand and forearm dimensions). In utilizing RCB as a point of reference, future students can more easily add and remove aspects of the current model to ensure that all desired design aspects are incorporated. Additionally, the prosthetic arm must be scalable to fit a range of body sizes. The methodology to ensure the prosthetic arm is scalable will be accomplished via SOLIDWORKS configuration tables, allowing the end user to easily scale the arm to their desired size using RCB as a datum. Additionally, the prosthetic arm must be made of easily sourced electronic components to ensure feasibility of assembly. Lastly, for ease of use in future studies, all documentation must be uploaded to a free public repository for universal access.

Customer Identification

This project is intended to be open-source, providing a high-quality prosthetic hand at the cheapest cost possible for the customer. The goal is to bypass the need for mass-manufacturing or third-party resale and market directly to the consumer. Therefore, the only main form of customer at stake is the direct consumer of the product. These would be individuals who are missing a hand/limb anywhere up to their forearm region. Due to the nature of the product format (including a multitude of .STL files), consumers would either need to have their own 3D printer with appropriate polyethylene terephthalate glycol (PETG) and thermoplastic polyurethane (TPU) filaments, or have access to said resources in areas such as local schools or maker spaces.

QFD Discussion

To fully analyze the design, a Quality Function Deployment (QFD) method was utilized to provide objectives for the final product to meet. Several criteria were used to compare the final product to the two current KSU prototypes that were presented at the beginning of the semester, as well as to the *open bionics* Hero Arm (see Appendix B for the full QFD.) The criteria were chosen because they are aspects of the arm that are of significant importance to the consumer regarding functionality, maintenance and convenience. Some of the main criteria that were used are cost, scalability, ease of assembly, and ease of repair, among several others. These criteria were ranked from a scale between one, being the poorest rank, and five, being the highest rank. Additionally, each criterion was assigned a "Kano Classification" of either "basic," "performance," or "excitement." A "basic" classification indicated that the criterion was a crucial design consideration, whereas an "excitement" classification indicated that the criterion was to be considered a feature that would be nice if possible, but not imperative to the customer.

As there were 19 criteria with a possible maximum ranking of 5 each, the highest possible total score was a 95. To obtain a datum of a minimum required score to achieve for the prototype, a "customer desired rank" was created by researching what was imperative to the final design and what could be sacrificed due to time [6]. For example, it was determined that the customer would be content with the noise level of the final prototype being somewhat loud (ranked a 1/5) while preferring the strength and reliability of the arm to be of quality (ranked 5/5). After totaling this subjective datum ranking, the customer desired rank was found to be a total score of 69/95. After a subjective evaluation between previous models and the final prototype, the final prototype was deemed to have a score of 61. This is less than the *open bionics* Hero Arm (77) but close to the customer desired rank of 69 [5]. As the final prototype did not have the same resources that the *open bionics* model does, it makes sense for it to score lower, but still be near the customer desired specifications.

The scores that were given to each model are subjective and were gathered from personal testing as well as reading into the descriptions of the model. This ranking method helps compare the different models and creates a standard for the final prototype to meet.

Assumptions

Assumptions made for the design process are that the consumer will have access to a computer and an internet connection to obtain the design files and relevant information. Additionally, the consumer will need to have assistance assembling the arm. Access to a 3D printer will also be required, as much of the model is 3D printed. If any alterations to the default functions of the arm are desired to be changed, the consumer will need to have knowledge or experience with 3D modeling software as well as coding experience. Lastly, the consumer will be required to read and follow the instructions and details of the product for optimal performance.

Function of Product

The function of this prosthetic arm is to provide the user with the ability to grab small objects from various different approaches. The grip comes from five fingers closing on the given object, providing five points of contact against the palm. To help the user pick up objects from different approaches, the wrist will rotate about two different axes; one axis is along the forearm and the other axis cuts through the wrist perpendicular to the previous axis, see Figure 3 a reference to the axes mentioned.

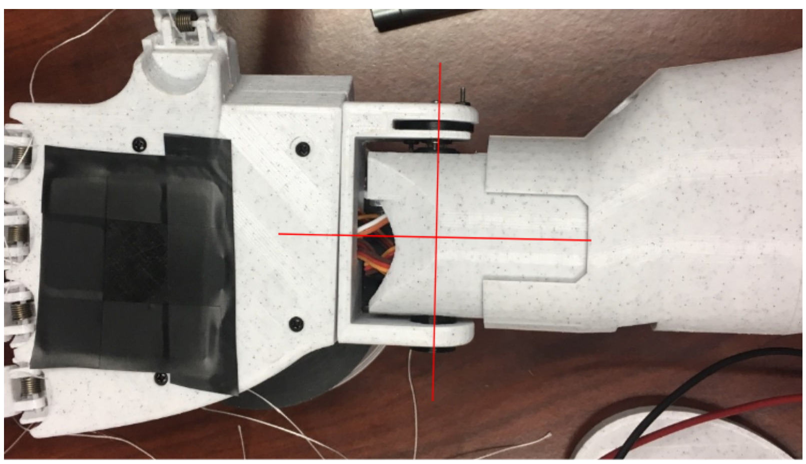

Figure 3. Axes of Movement for Wrist Component

Form of Product

The product consists of five fingers, resembling a typical hand. Four of the fingers consist of three segments and three points of rotation including the connection to the palm. The thumb has two segments and two points of rotation including the connection to the palm. There are four small servos placed in the palm: each pulls an end of a string into a spool which is fed down the length of the finger to pull it closed. All fourteen finger joints mentioned above have a torsion spring to pull the finger back in line when the servos release tension on the string. Each finger and the palm also have some form of TPU grip-assisting substance attached at the expected points of contact. The palm has a bracket extruded off the base,which is attached on one end to a servo and on the other end attached to a stabilizing post to allow for rotation. The wrist portion acts as a housing unit for the last servo and it is attached to another servo that is mounted to the forearm. This is mounted such that the wrist rotates around the axis that runs along the forearm while the forearm remains fixed.

Conceptual Design Discussion

i. Fingers and Joints

Fingers and joints were the first portion of the prosthetic arm to be designed. A life-like prosthetic was a key design objective, therefore design began by studying the basic anatomy and aesthetics of a hand. To imitate a standard hand, all of the fingers were made having three sections and the thumb having two sections. However, the main focus was on function instead of aesthetics, so aesthetics were held off until the main function of the hand was successful. The main topic focused on the interlocking of the fingers segments and palm, ensuring adequate articulation without kludgy and unnecessary additions.

From the previous designs, there were both ideas to take away and components to stay away from. As previously shown, Figure 1 illustrates a design with TPU as the connecting material between joints. These fingers are extended open using the TPU structure and its natural flexibility. The fingers are flexed closed into a fist by pulling on strings via a motor. Figure 2 shows a design where the fingers are connected by a pin system. Two strands of fishing line tied to the fingertip control the flexion and extension of each finger. One line runs down the front of each finger to control the closing of the hand, and the other strand of line controls the opening of the hand.

The string method for opening and closing the fingers was chosen, as it seemed a simple and effective way for flexion. However, the simplicity of only having one strand of string from each finger to control the whole hand was appealing, thus a design combining the string and TPU joint was initially implemented. TPU would provide the spring-like opening of the hand due to its flexibility and strength. Each finger piece was to have an identical end point, besides the tip of the finger, so the consumer could print a multitude of 'connectors' that work universally with all parts of the hand. The file name for the connectors was 'DogBone' due to its side profile shape seen in Figure 4. There needed to be a space for the string to run through the front side of the finger, in addition to a place to tie the strings to the tip of the finger. Looking at each finger piece from an elementary view, the length of each joint as well as the diameter matched that of RCB's hand, see Appendix A.

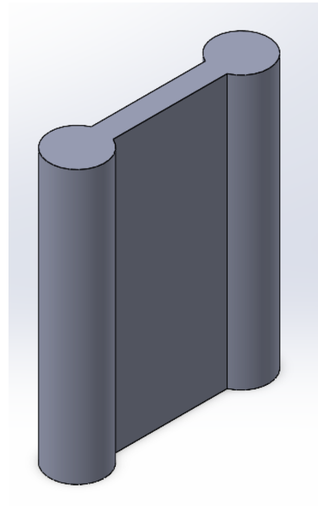

Figure 4. Dog Bone Connector

The larger circles on each side of the dogbone would fit into each piece of the finger and hold them together (see Figure 5 for the dogbone slots on each end of the finger piece). Resulting range of motion of the fingers was impressive, but there were a couple of issues with this design. First, gravity was working against the hand; the tensile strength and flexibility of TPU is incredible, but the material is not as good at forcing joints open after continued use, similar to the way a spring wears down. The second issue was that it elongated the fingers by approximately 30%, straying from the goal of resembling an actual hand.

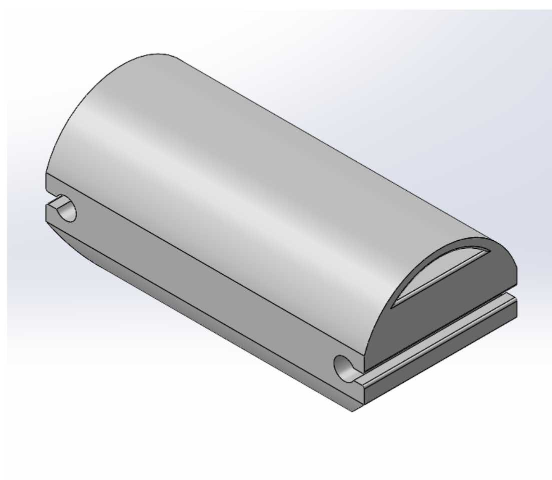

Figure 5. Finger joint old version

The plan after TPU joints was similar to Figure 2; a string on the front side and back side of each finger to control the closing and opening of the palm. This did not change the design of the actual fingers much, besides making sure that there were paths for strings to go on either side of each finger piece.

What did change was the means for each finger to connect to one another. There was a large amount of editing done on each piece to allow a pin to combine them to one another and allow them to freely rotate from approximately 0 to 90 degrees. Contact with the backside and frontside of the conjoining finger was to be the limit of range. This design was promising during initial testing while the fingers were not connected to the palm, and the strings were not connected to the servos. Issues later arose with this design due to the servo motors only rotating 180 degrees. More information on how the motors curled the fingers can be found in the palm and electronics section below. The radius of the spool limited the distance to which the string could retract, reducing finger flexion to 60% of a fully-curled finger.

In addition to the fingers not fully curling in, there was also trouble with the fingers straightening. With this more complex design, there were a total of ten strings tied to four servo spools, and the palm quickly became a tangled mess.

Resultant of these issues, the team decided to move forward with one string to curl the fingers in, and torsion springs to flex the fingers back to a straight, open, position. A pin system would still be the means of connecting each finger piece, and a torsion spring would sit in the joint and surround the pin. The springs ordered had to meet multiple requirements: they needed to be small enough to fit in the gaps between finger pieces, large enough to surround the pins, strong enough to flex a whole finger straight, and be weak enough to allow a servo motor to overcome the tension, see Prototype Details: Section ii. Overview of Analyses - *Selecting Torsion Springs* for the determination of torsion spring specifications.

Each finger piece had to be altered to account for torsion springs. A chunk was taken out of each piece near a joint and a hole was added for the leg of the spring to be inserted into (see Figure 6).

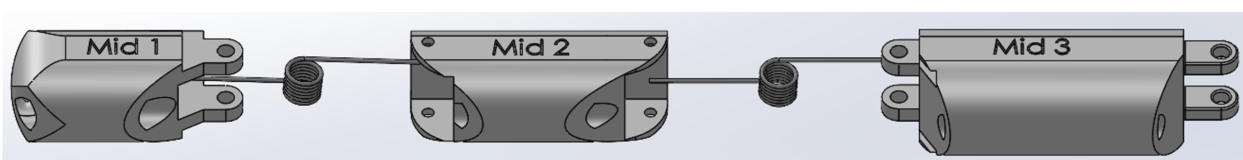

Figure 6. Exploded View of Final Finger Design with Torsion Springs

This model finds the sweet spot between simple and effective. A recommendation could be made to reduce the number of parts for each finger. With this pin and spring system there are nine separate parts for the pointer, middle, ring, and pinky fingers.

ii. Palm

From the previous designs, the palm and wrist housed no electronics as both served only to route string from the fingers to the forearm where the servo motors would be mounted, see Figures 1 and 2. However, as the intended use for these prosthetic designs remain vague, all sections of the prosthetic arm remained independent of one another. For instance, the palm was designed to house all the electronics required to actuate the fingers, thus, if the end consumer only had an amputated hand, they would be able to download and use the prosthetic hand portion of the design. This is similarly the case for the wrist, forearm, and elbow as each part is segmented dependent on the intended use case.

Initially, the palm was designed as a rectangular box with minor curvature to mimic the general outline of a palm, see Figure 7. However, as testing for the fingers began, issues with how the finger rested with the palm arose due to gravity causing the fingers to relax past the top of the palm. Thus, small extrusions were placed at the base of each finger to replicate knuckles, see Figure 8.

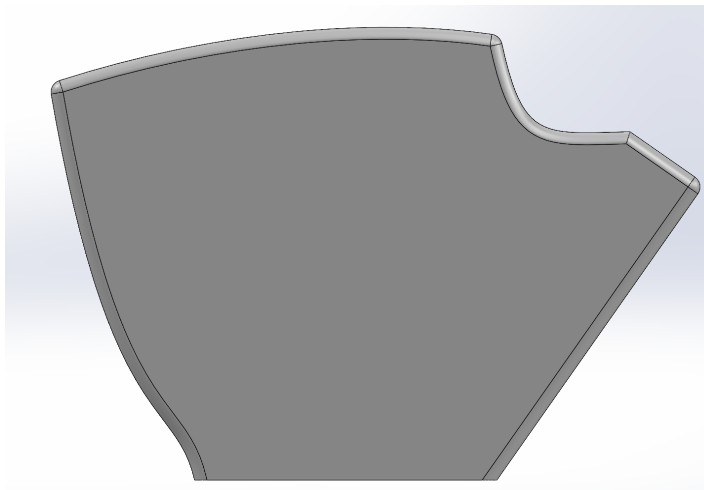

Figure 7. Preliminary Palm Design

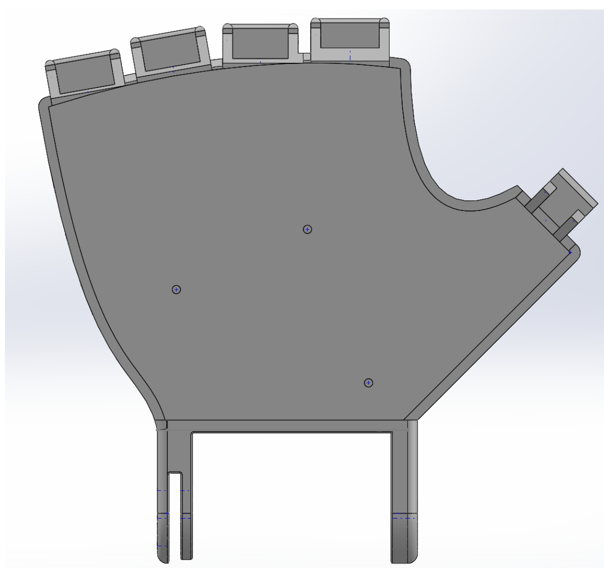

Figure 8. Palm Design with Added Knuckles

During testing, grip issues also arose as the thumb was placed in a manner that did not bisect the rest of the palm, see Figure 9. As a result, a small curve was added to the base of the palm to allow the thumb to more easily reach the center and assist in grip, see Figure 10. Additionally, the square knuckles were replaced with a more circular shape as the aesthetics of the rectangular extrusions were subjectively not pleasing to RCB.

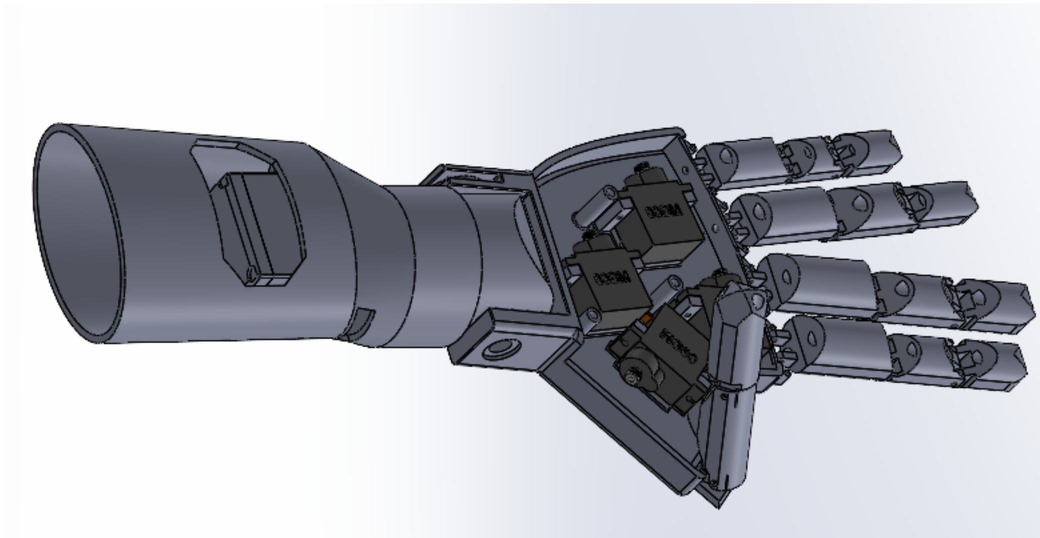

Figure 9. Thumb Range of Motion Issues

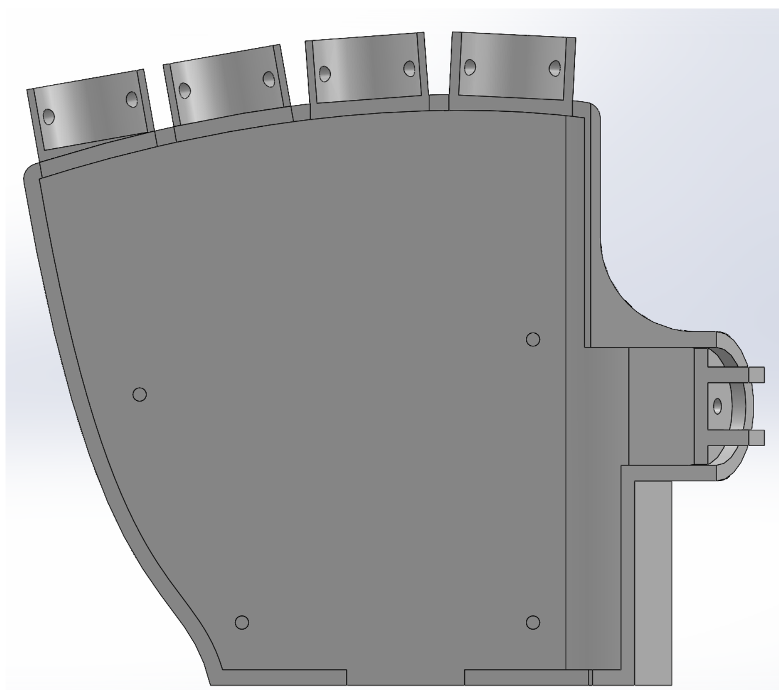

Figure 10. Rounded Palm for Better Thumb Range of Motion

In tandem with the palm iterations, a servo motor mounting sled was also created that would be placed in the palm above. Due to the lack of room in the palm, only four servos would be used, with one servo controlling the middle and ring finger and the remaining three servos controlling the remaining three fingers. Figures 11 and 12 illustrate the sled with the flat palm and curved palm respectively.

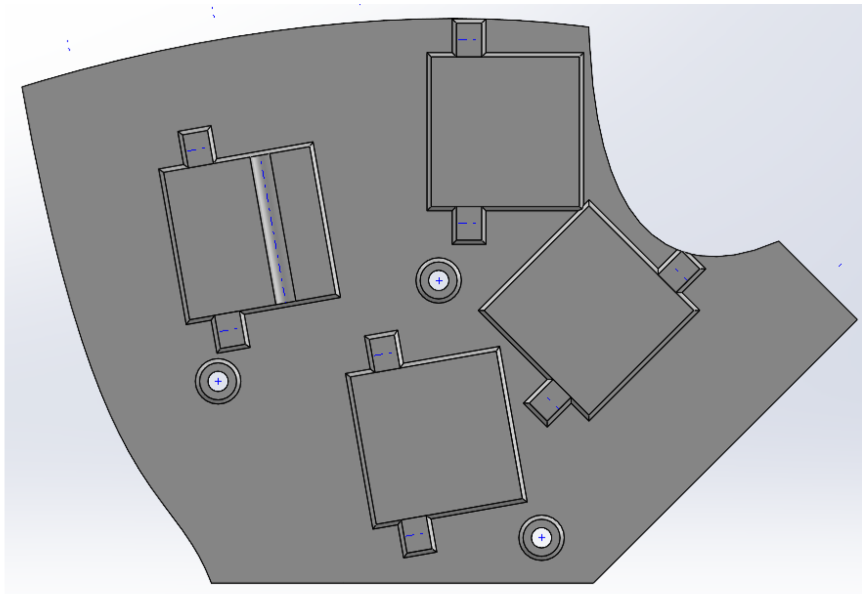

Figure 11. Servo Motor Mounting Sled for a Flat Palm

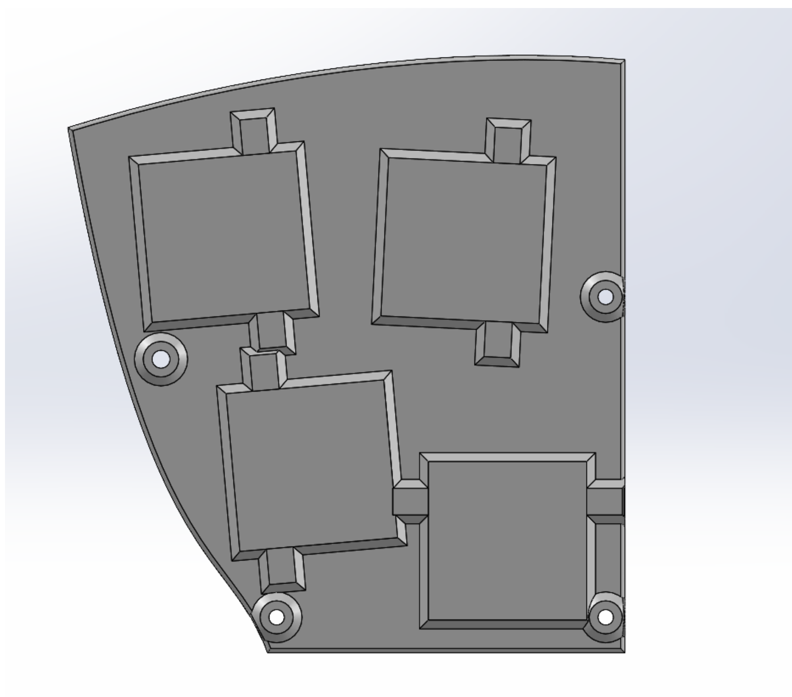

Figure 12. Servo motor mounting sled for a rounded palm

Although no direct issues arose from the servo mounting sleds, the spools mounted on the servos were iterated heavily as the shape and dimension of the servo spool dictated the amount of movement in each finger. This was due to the spool diameter directly correlating with the distance pulled via the strings in the fingers. As a result, the spools initially had a small hole drilled out for the string to be terminated to, see Figure 13. However, after testing, it was determined that the spools must contain a small groove to allow for the string travel distance to more adequately match the diameter of the spool, see Figure 14 and , see Prototype Details: Section ii. Overview of Analyses - *Servo Spool Diameter* for the determination of required spool diameter.

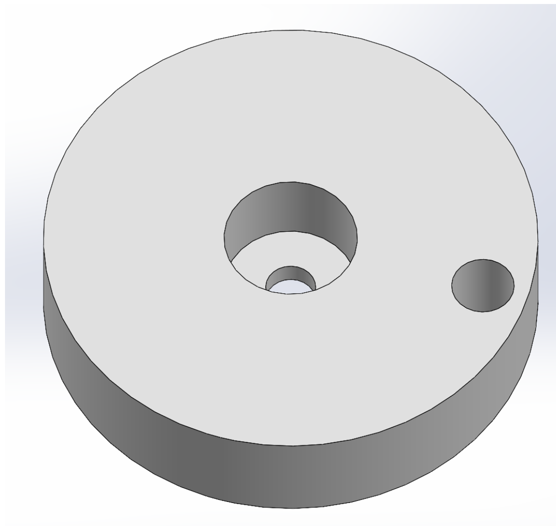

Figure 13. Servo Motor Spool with No Rounded Grooves

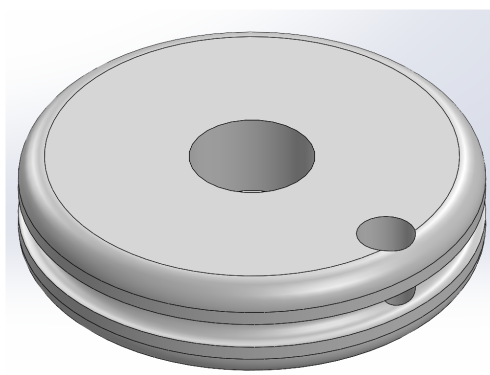

Figure 14. Servo Motor Spool with Rounded Grooves

Lastly, a lid was fitted to the base of the palm, matching all curves and closing any gaps that arose. Five cutouts around the exterior for the fingers to fold into. Additionally, a small cutout was placed near the center of the palm as a mounting location for a pressure sensor as, during testing, this location was determined to be near where all the fingers actuated to, see Figure 15. To protect the pressure sensor, a small pad of TPU was fitted to the cut out to ensure a friction fit that would easily transfer force to the sensor while ensuring no damage to the electronics.

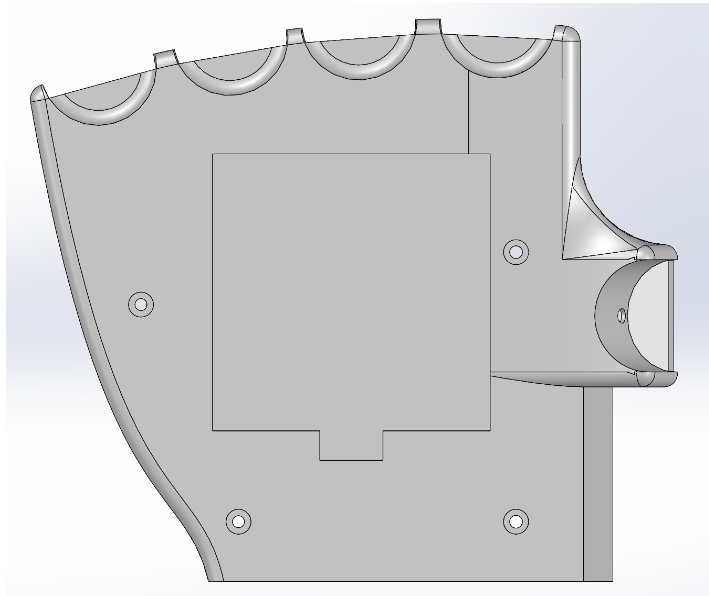

Figure 15. Palm Lid with Pressure Sensor Cover

iii. Wrist

To begin designing the wrist, research was conducted by viewing previous reports and ideas produced by other prosthetic arm efforts. It was noted that many 3D prosthetic arms don’t utilize wrist rotation or up and down movement, presumably due to simplicity. However, our design had the requirement of wrist movement. The most compelling option with wrist movement was from bioRxiv featured two degrees of freedom from two servos acting normal to each other. This concept was simplified and is seen in Figure 16 below [8].

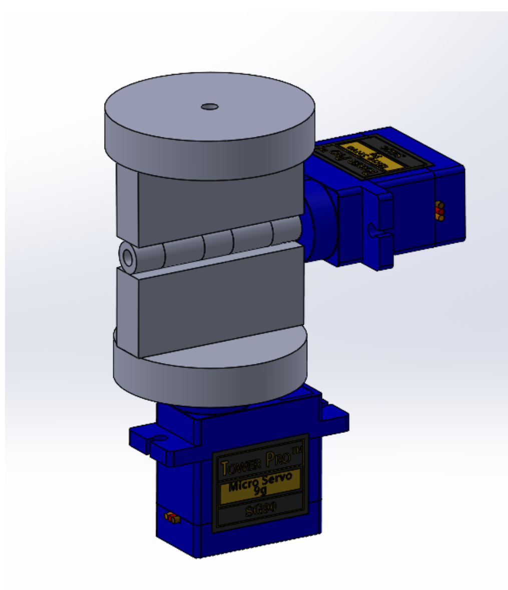

Figure 16. Initial Concept of Wrist Articulation

Once this initial concept was chosen, the next step was to determine which servos should be used in it. After browsing websites such as McMaster Carr and Digikey, the MG996R servo was chosen due to its high torque and relatively low profile (see Appendix C, Figure C2). The next step was to create a functional housing for these servos that would resemble a wrist and be integrated with the forearm in some manner. Bolt sizes were derived from the maximum allowable size, based on the mounting holes in the servos and servo horns. A preemptive design including the servos is shown in Figure 17 below. The bottom servo would be fixed inside of the forearm, which would be in charge of rotating the wrist cylinder located above it. This wrist cylinder would be fit inside of the forearm that would provide it strength against shear force. Normal to this cylinder would be the wrist to palm connector attached to both the servo in the wrist cylinder and the palm, allowing for up-and-down movement of the wrist.

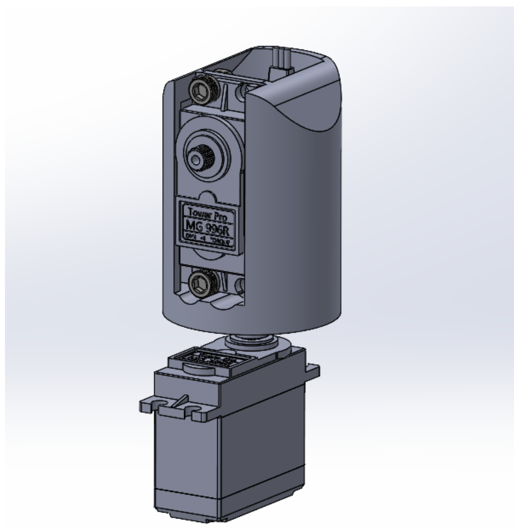

Figure 17. First Printed Model of Wrist Articulation

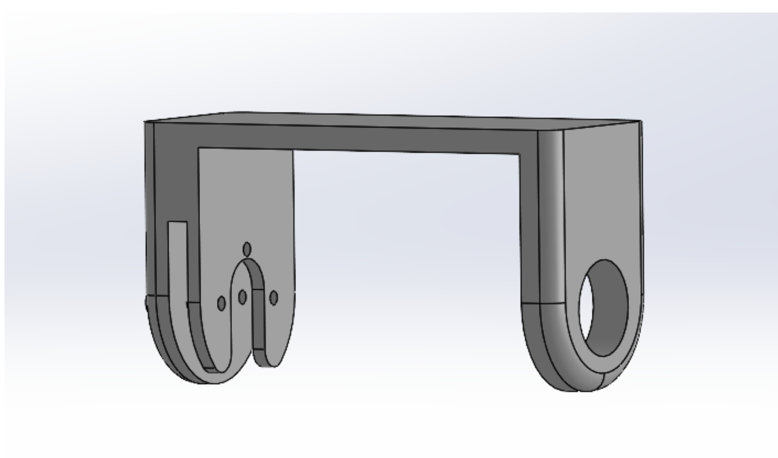

Figure 18. Wrist to Palm Connector

Figure 18 shows the concept behind connecting the top wrist servo to the rest of the palm. On the left side of the figure, is the slot and mounting holes for the servo horn. The round servo horn which came with the MG996R servo was used in this slot. Four 0-80 bolts and nuts were used to attach the connector to the servo horn, and servo. On the right, is the hole for the bearing to go through. The final assembly, and exploded view of the wrist mechanism will make this more clear. Figure 18 shows this as an individual part, but this is combined with the palm when printed so it is one part as shown in Figure 8.

The first attempt at designing the bottom wrist mount is shown in Figure 19. This design had many flaws since assembly was impossible, but the main concept was carried throughout the whole design process. Things that made assembly difficult included: not having a cut out at the top for the top servo to slide into, minimal access to screws for the bottom servo, and it did not need to be incorporated into the forearm. In later versions of this design, the bottom wrist mount shrunk to about half the size, which is shown by Figure 20. Improvements made to the final version include: the top servo slot, hex holes, three connection hex holes to mount to the forearm. It is worth mentioning that the top diameter of the “bottom wrist” is only 0.030 inches bigger than the top wrist of Figure 17. This is to prevent the bottom rotational servo from being over-torqued from a side to side load case. Unfortunately, the entirety of the wrist design is not scalable without replacing the MG996R servo motors.

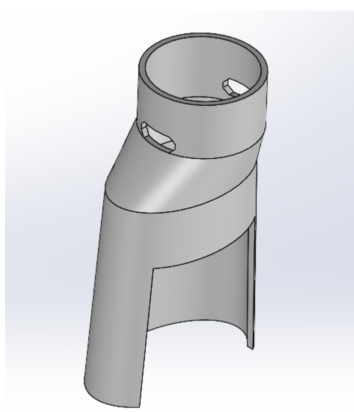

Figure 19. Bottom Wrist

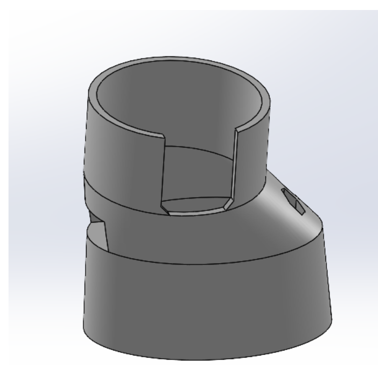

Figure 20. Final Bottom Wrist

Throughout the design process of the wrist mechanism, the biggest challenges were ease/time of assembly, interference issues, and figuring out the correct assembly process. Many minor tweaks to the design were made to simplify assembly, however due to the use of the two servos within a small space, many screws had to be used. Snap fitting features and other quicker mechanisms were not considered, primarily due to the reliability of screws and nuts when fastened tightly. It is highly recommended that any individual trying to assemble this design orders a screwdriver set that comes with over fifty interchangeable bits. Some bolts require allen keys, others require a phillips bit. The 8-32 bolts were chosen to be allen type bolts due to the ease of torquing a bolt with an allen key compared to phillips.

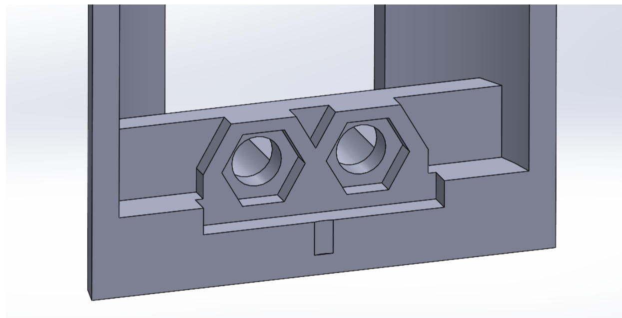

Figure 21. Initial Attempt at Securing Nuts

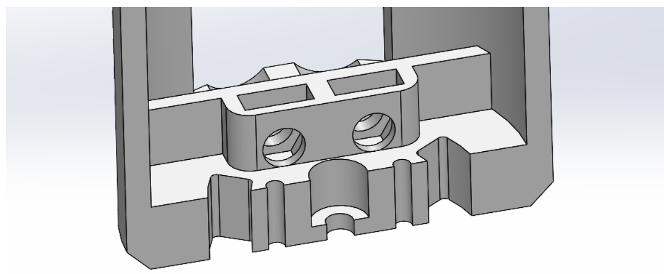

Figure 22. Final Method of Securing Nuts

The incorporation of the constraint of nuts into the design was used all throughout the wrist and forearm design, to improve the already complex assembly process. The part shown in Figures 21 and 22 is the top wrist from the inside via “Section View”. It displays the bottom servo mounting screw which is a blind hole. As you screw the servo in place, there is no way to hold that nut down on the backside since the servo is above it. The first method from Figure 21 was a valid attempt to hold the nut in place while fastening the bolt, however the bolt would push the nut out of the hex hole. It was possible to tighten it fully with the Figure 22 configuration, but it was not consistent and very difficult. The method of Figure 22 was a good fix, as it allowed the nut to be constrained properly while the bolt was fastened. One issue of both designs is the need to remove the support material in the holes, which can be difficult depending on printer settings and filament type.

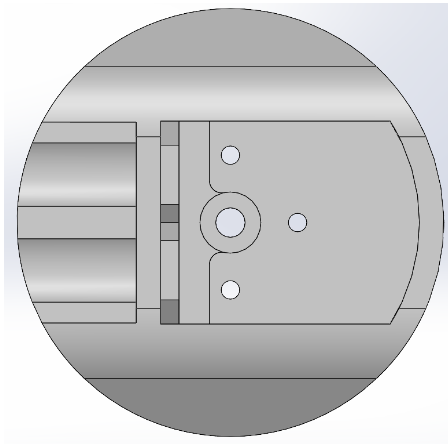

Figure 23. No Wire Cutouts

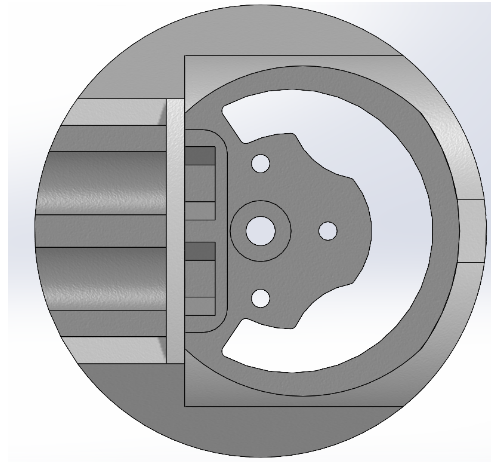

Figure 24. Top View of Final Top Wrist

Many things were not considered in the original versions of the wrist concept. Routing wires through the wrist was one of those things. Since there are four servos in the palm plus a force sensor, there are five three wire connectors coming out. Figures 23 and 24 show the original design of the top wrist and the eventual large opening made for the wires of the final top wrist design.

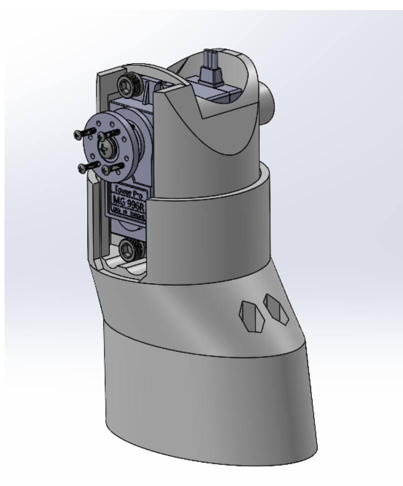

Figure 25. Final Wrist Isometric View

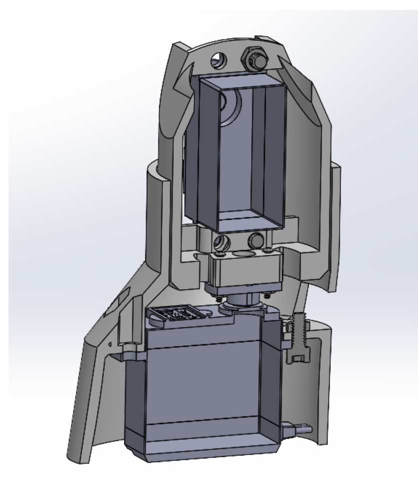

Figure 26. Final Wrist Section Cut

As seen above, the final design of the wrist assembly is shown in Figures 25 and 26. Connections to the palm and forearm are all bolted. Not all bolts and nuts are modeled to save load time within Solidworks. As the arm was designed to be a right arm, the wrist was chosen to be lofted to the left to follow the natural inward-leaning profile of a right arm.

iv. Forearm and Elbow

To begin construction of the forearm, sizing was based on RCB's dimensions (see Appendix A, Figures A1-A4). The basic shape of this forearm followed a loft between two planes corresponding to the length of his forearm, guided by two ovals the size of his wrist and elbow. The centers of these two ovals were placed at a horizontal distance of 1.5in. to replicate the natural inward curve of an arm. The two planes were offset at a dimension corresponding to L1, L2, and L3. Due to the similarity of all three of these dimensions (two being 11 inches, and one being 10.5in.,) the plane offset was simplified to be 11 inches normal to the original plane. This loft was then hollowed out with the "Cut Loft" command to a thickness of 0.3in. To gain access to the inside of the arm, a rectangle was drawn above the arm and then the SOLIDWORKS "Extrude Cut" - "Up to Next" command terminated the cut upon reaching the interior of the shell. This access was designated for the storage of electrical components including breakout boards and bread boards, any necessary microcontrollers or power regulators, and power supplies. The outcome of this process is seen in Figure 27 below.

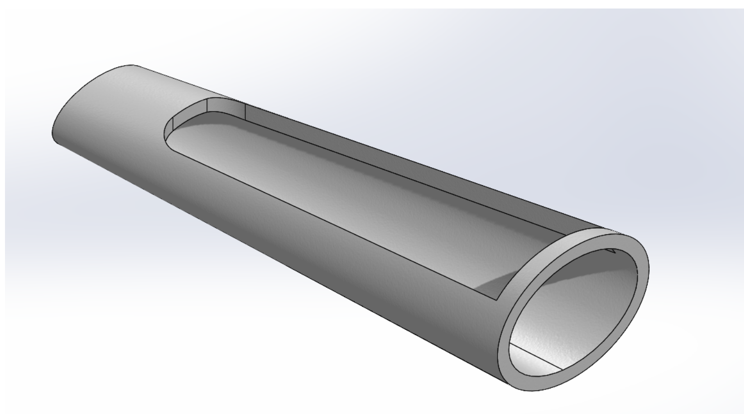

Figure 27. Forearm Design Isometric View

Taking into consideration there is a wide variety of 3D printers on the market with varying build heights, it was determined that the forearm should be printed in two separate pieces and then joined together. This ensures that any consumer could print this product regardless of the quality of their printer. The first iteration of the forearm was created with three male-to-female joints at the ends in the hope of a tight friction-fit connection as illustrated in Figure 28. However, these joints were nowhere near strong enough to support much force and broke promptly.

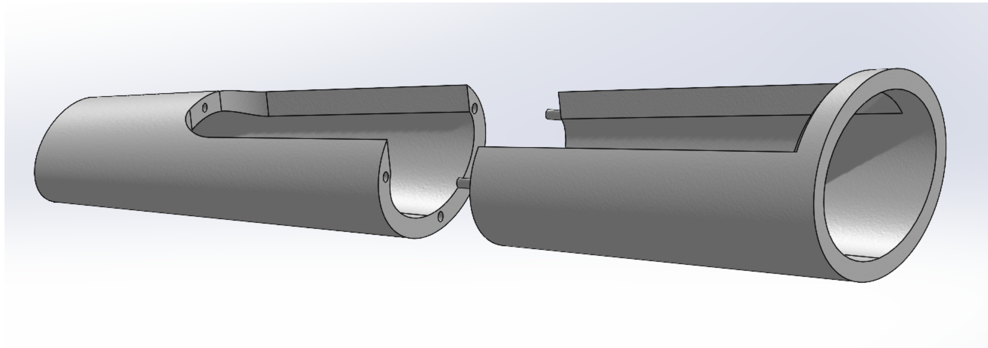

Figure 28. Illustration of Male-Female Connection of Forearm

For the first redesign of the forearm, the thickness of the shell was decreased to 0.1in. The previous thickness of 0.3in was far stronger than necessary and was therefore wasting both filament and space for interior storage. This redesign also featured anchor points for a nut-and-bolt connection at the halfway point as seen in Figure 29, which would be much more secure than the previous male-to-female connectors. Furthermore, to accommodate the evolving wrist design, the front of the forearm was designed to fit the wrist joint, with a mounting point for the servo. The full assembly of this iteration is seen in figure 30.

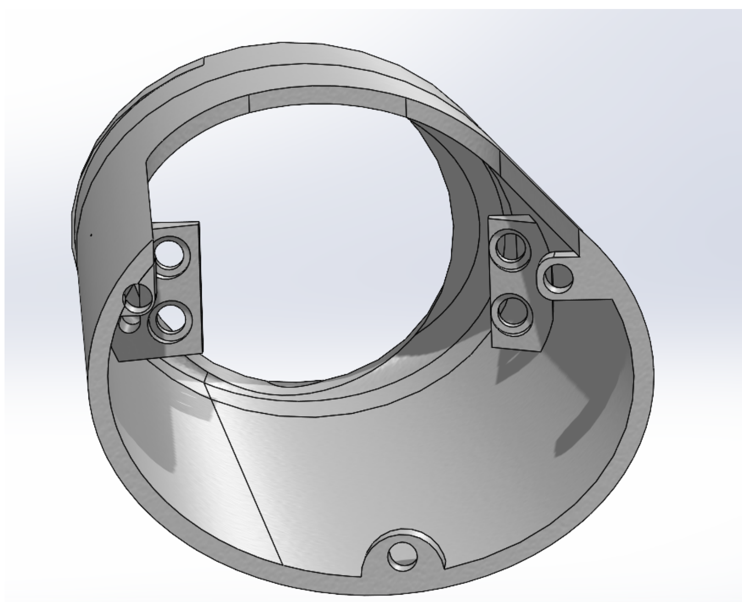

Figure 29. Forearm Redesign to Fit Wrist and Bolts

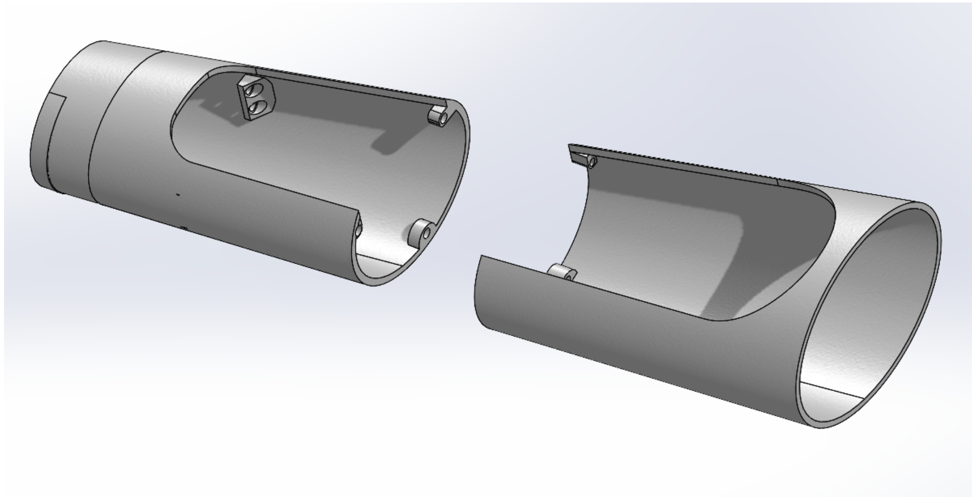

Figure 30. Isometric View of Updated Forearm Version 2

Upon printing this new design, multiple flaws were shown. For one, the wrist being directly inserted into the forearm had too much excess room to rotate, and had little support around its axis to combat potential shear force. Furthermore, the bolt joints were too thick for the bolts to go through. Realizing that the wrist components would not be scalable anyway due to servo sizes and their mounting, it was decided to make the wrist its own separate piece and to not pursue integration inside of the forearm. This concept is featured in Figure 31 and was the final design concept for this component.

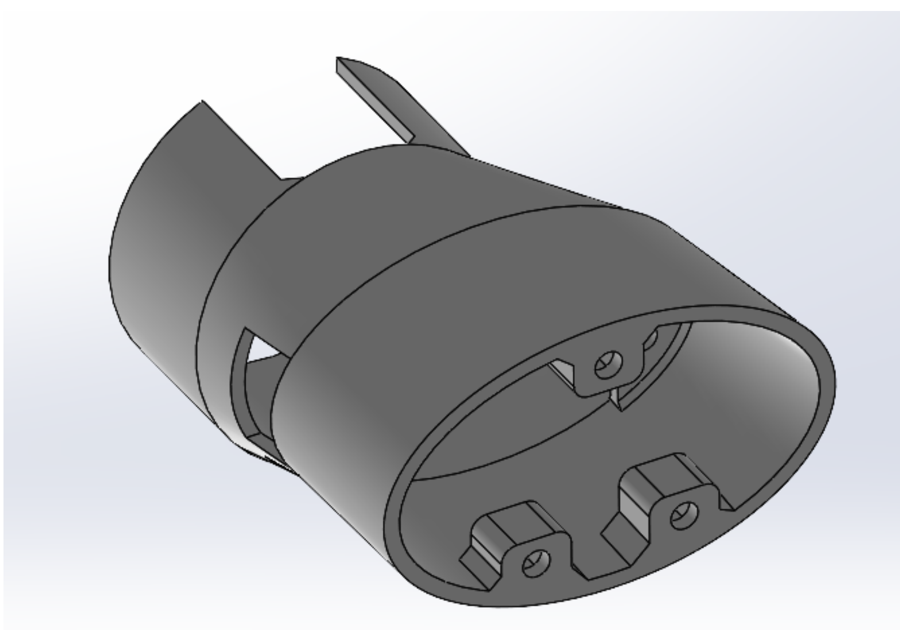

Figure 31. Wrist Connector

With this new individual piece for the wrist connection that is unscalable, a set circumference could be used for the front portion of the forearm.The added length provided by the connection also allowed for the forearm to be shortened, and eliminated the need to split it in half to be printer-friendly. Bolt connections utilizing the 8-32 bolts and nuts were created at the front and back of the forearm, in addition to the back to account for the elbow endplate discussed in the following Elbow section. This new forearm and wrist assembly was then printed out with the elbow mount for an assembly check as seen in Figure 32.

Figure 32. Elbow, Forearm and Wrist Assembly

This version of the assembly seemed promising at first, but it was soon realized that there would not be enough room lengthwise to fit all of the wiring in addition to the Arduino, buck converter, and breakout board. This prompted a final redesign of the forearm with cutouts at the back in addition to an extended cutout at the top, reaching all the way to the bolt connections on either side as seen in Figure 33.

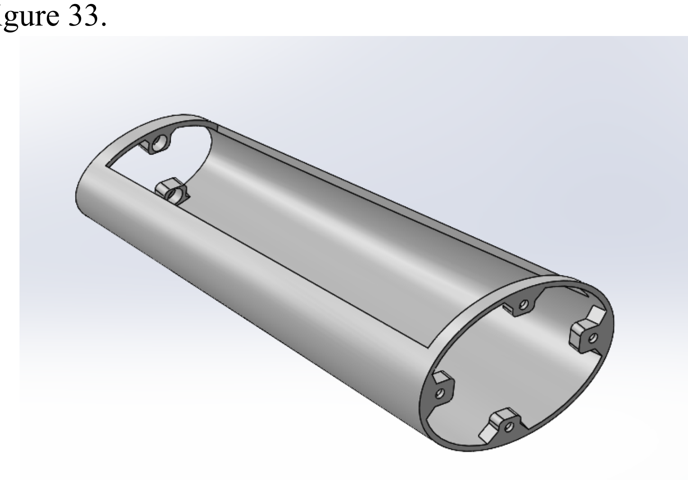

Figure 33. Final Forearm Design

In anticipation of covering the electronics contained within the forearm, a cover was designed with cutouts for the buck converter screen and two holes for the power switches intended for the Arduino and servos. As seen in Figure 34 the cover is the negative profile of the forearm shell and is designed to fit snugly over the top of the open area. Due to time constraints this cover was intended to be either taped or glued onto the forearm. Ideally, there would be a hinge system or magnetic connection of some sort for convenient access for repairs.

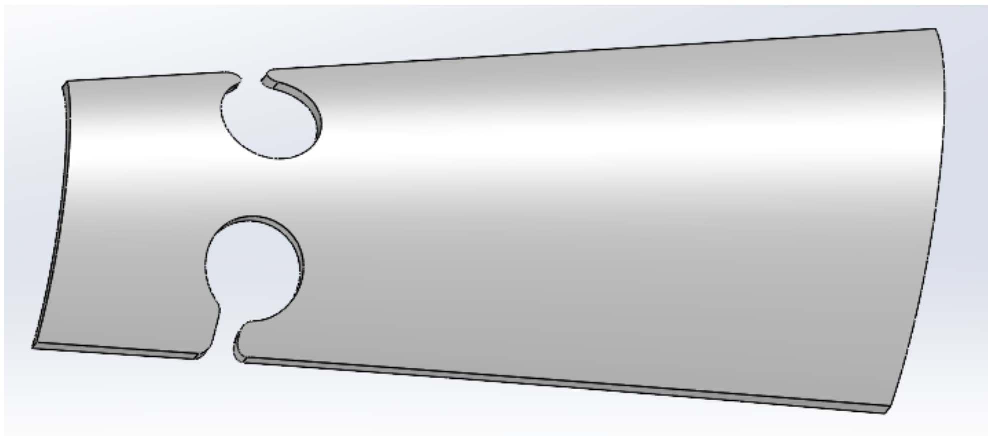

Figure 34. Forearm Cover

Elbow

In practice, this arm would fit to the residual limb of the customer. Although not an explicit feature of the prosthetic arm, an elbow was created to mount the arm to a fixed stand and more closely demonstrate the arm's strength and functionality. This was done by modeling an endcap to mount to the wider end of the forearm which featured extruded tabs to carry spur gears. These spur gears would join matching spur gears attached to two servos on a mount shown in Figure 35.

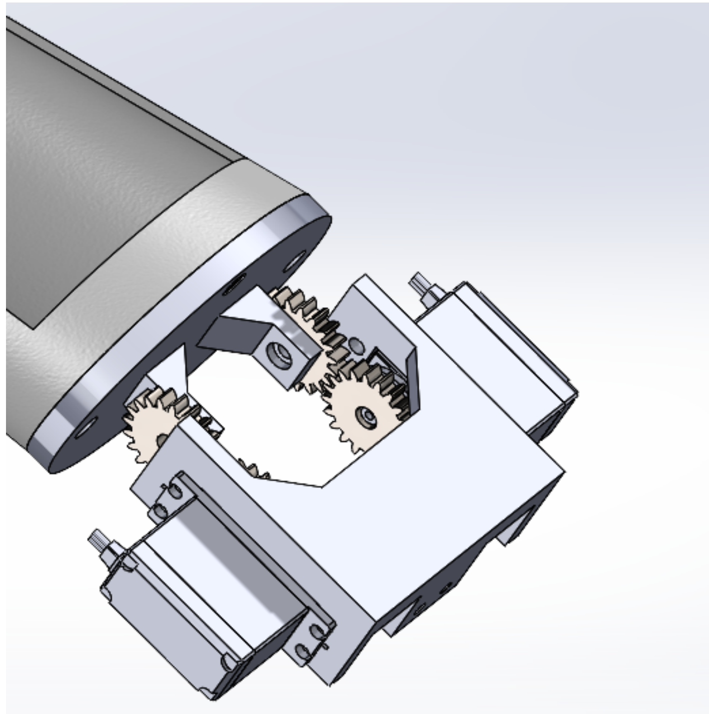

Figure 35. First Elbow Mount

After printing this assembly and testing it, it was determined that the two MG996R servos were competing with each other. Due to servo timings, one was firing slightly before the other, causing the internal gears to fight and prompting a redesign featuring only one servo. Also included in this redesign was a wider mounting base orienting the MG996R parallel with the wood fixture, as well as integrating the endcap spur gear into the part itself as seen in Figure 36. The spur gears were created at a 3:2 gear ratio to assist in torque management.

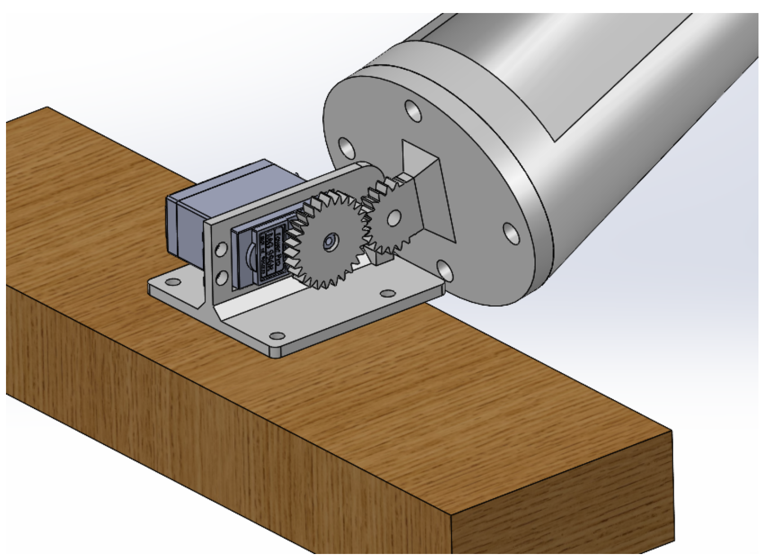

Figure 36. Elbow Mount Redesign

However, with only one servo, the overall weight of the arm proved to be too much torque to handle and this resulted in the servo overheating and stalling. To resolve this issue, a new servo (DSServo 35kg servo motor) was ordered, see Prototype Details: Section ii. Overview of Analyses - *Gear Ratio Selection* for the determination of the required gear ratio to move the arm assembly (see Figure 37 for the gear attachment).

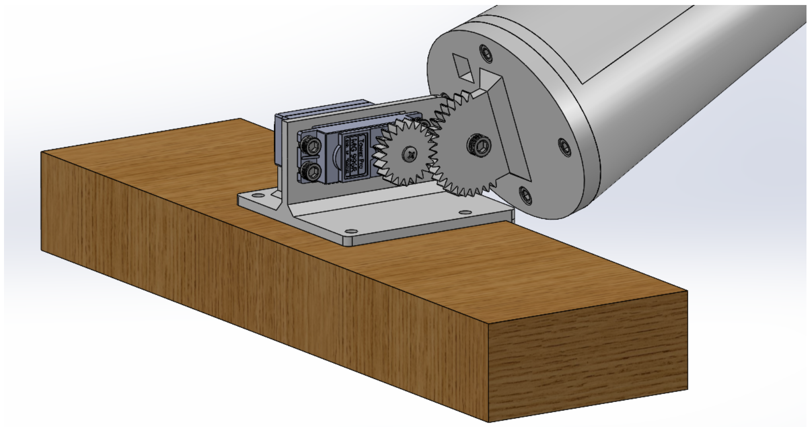

Figure 37. Final Elbow Gear Design

v. Electrical Components and Program

As a key deliverable required the prosthetic arm to be capable of lifting a cue ball, all electronics were sourced to ensure that this feat was possible. For the prototype, due to geometric (i.e. area and angle of impact) and physical (i.e. mass and size) concerns, electronics were chosen with specifications higher than required. MG 90 servo motors with 1.8 kg.-cm.. of torque at 6V were selected to articulate each of the fingers as the max weight one servo must carry is 0.12 lbs with an additional competing torque of 0.402 in.-lbs. from three torsion springs (see Appendix C, Figure C1 for the technical specifications for this motor) [9]. These motors have a stall torque of 2.2 kg. -cm., which would be more than required to lift a 7.4 oz (0.209786 kg) cue ball, but are reliable and small enough to be housed in the palm, thus the servos were used as the motors for the fingers [10]. Thus, as the footprint of the servo sled must fit within the palm, four of the MG 90 servo motors were to be used, with one servo pulling both the middle and ring fingers as the overall torque is well above the necessary amount to lift a cue ball and the fingers. Next, MG996R servo motors were selected to be placed in the wrist with a torque of about 9.55 kg.-cm. at 6V, which would easily be capable of lifting any object placed in the hand so long as the object was under the cumulative rated mass of the MG 90s placed in the palm, with an approximated max weight of 3.5 lbs. (again see Appendix C, Figure C2 for the technical specifications) [11]. Two of the MG996R servo motors were placed in the wrist, with one servo serving to rotate the hand around an axis parallel to the forearm, and the other having the purpose of bringing the hand perpendicular to the forearm. Additionally, as the torque from the servos motors are much higher than the force required to grasp an egg, pressure sensors were tested to determine the most reliable sensors for ensuring the egg would not be crushed when the hand closed. Lastly, as the rated torque of the MG996R servo motors were under the required torque for a 20.5 in. 2.1 lb. complete assembly, a DS3235 35KG servo was placed in the elbow instead as the prosthetic arm is very front loaded, with much of the weight far from the elbow (in the hands and wrist) (see Appendix C, Figure C4 for the technical specifications of the motor). Therefore, a higher torque servo was placed in the elbow to ensure that no torque issues would hinder the operation of the wrist [12].

Initially, a conductivity pressure sensor, “Walfront9snmyvxw25”, from Amazon was tested as the rated max weight was 2 kg and ,aesthetically, was small and easily hidden within a finger as the diameter of the sensor was 10mm [13]. However, current continuity was required to receive readings, thus, the object being held would also require a sensor, which was impractical as the consumer should not be required to carry sensors in order to move objects around. In conjunction with this, electronic noise and other defects in the sensor resulted in lighter objects giving erroneous values, see Figure 38. As such, a different sensor was selected to provide feedback to the circuit.

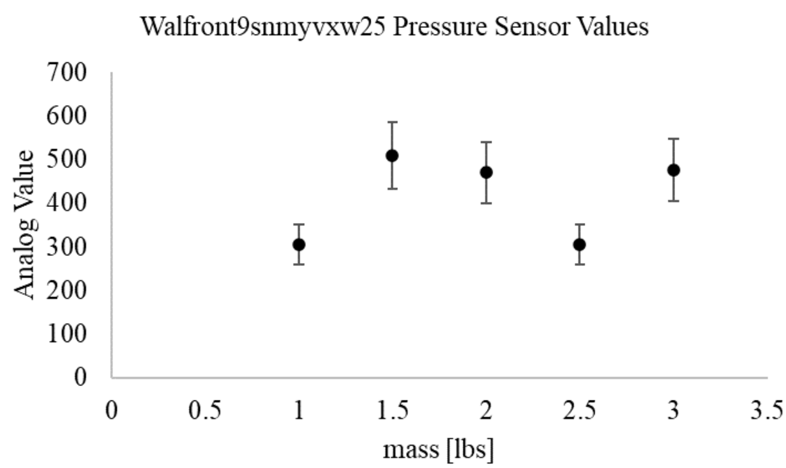

Figure 38. Walfront9snmyvxw Pressure Sensor Readings

The next pressure sensor, “FSR01CE” from Digi-Key, had a larger profile, 43.69 mm x 43.69mm, with a max weight up to 5 kg (see Appendix C, Figure C3 for full technical specifications) [14]. The pressure sensor detected mass via impressions on the sensor pad, thus not requiring a secondary sensor. In tandem, as the pad did not require a secondary pad to complete the circuit, the sensor values produced were closer to the expected values as the more mass placed on the sensor resulted in higher analog values, see Figure 39. Thus this sensor was used for the prototype, being placed in the palm close to the active area where objects would be resting.

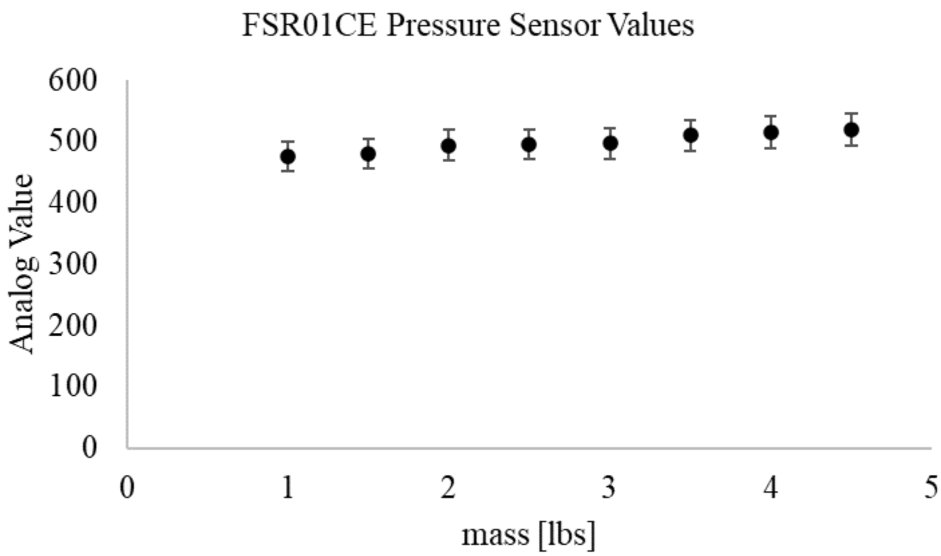

Figure 39. FSR1CE Pressure Sensor Readings

Next, total current draw was computed to determine an adequate power supply to operate all the electronics in the prototype. From the data sheet provided for the MG 90 servo motor, the idle current draw is approximately 10mA and the stall current draw is approximately 700mA [9]. Additionally, the MG996R servo motors require 10 mA at idle and 1500 mA at stall [11]. Thus, as there are four MG 90 servo motors and three MG996R with a maximum current measured at about 1.25 A +/- 0.30 A draw during testing, but upwards of 3 A if the MG996R did experience stalling. Therefore, a LM7805 linear voltage regulator was first used as a power supply as the circuit is able to produce 1.5 A which is just under the observed current draw (see Figure 40 for the circuit diagram for the LM7805). However, friction and load appeared to overcome the current limit, so an adjustable buck converter manufactured by DROC inventoried as “180080AFA” was purchased from Amazon to step voltages from 7.4 V to 5 V with 3 A. However, due to size constraints within the forearm, a smaller buck converter was purchased, capable of stepping down the voltage to 5 V, but with increased amperage output to 4 A.

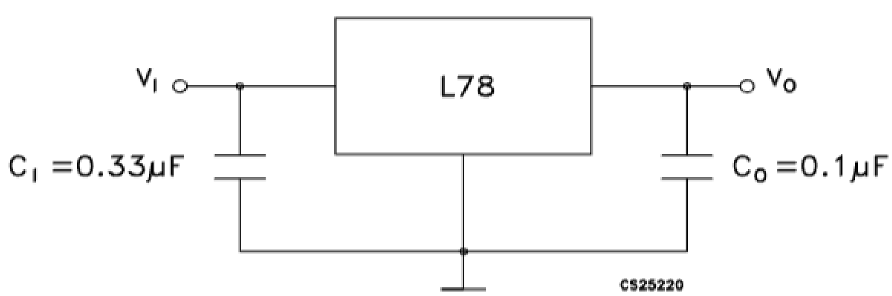

Figure 40. Sample Circuit for LM7805 Voltage Regulator[15]

Lastly, a microcontroller was selected to control all the electronics. As computational speed and voltage regulation are not heavily required due to the only control being the movement of motors, an Arduino Mega 2560 was selected due to the mass quantity in RCB's possession.

With electronics determined, a program was then written to communicate between a bluetooth module through an application called Dabble which would actuate servo motors in the hand, wrist, or elbow depending on the button pressed (see Appendix D, Figure D1 for the circuit diagram and Appendix D, Figure D2 for the logic diagram). The program also utilizes pressure sensor readings to articulate the servo motors in the hand until the force sensor reads values previously determined for grasping the egg and cue ball. Movement in the wrist and elbow will be manually executed using other available buttons (see Appendix D, Figure D3 for the movement diagram and Appendix E for the program used to control the prosthetic arm).

vi. Scalability

In order to make the design scalable, the dimensions were set up so that they shared a mutual datum. This was in order to have the dimensions scale from a mutual point to simplify the scaling of the design. As shown below in Figure 41, the datum for the palm was defined as the left and bottom most lines, with all subsequent dimensions referenced from these areas.

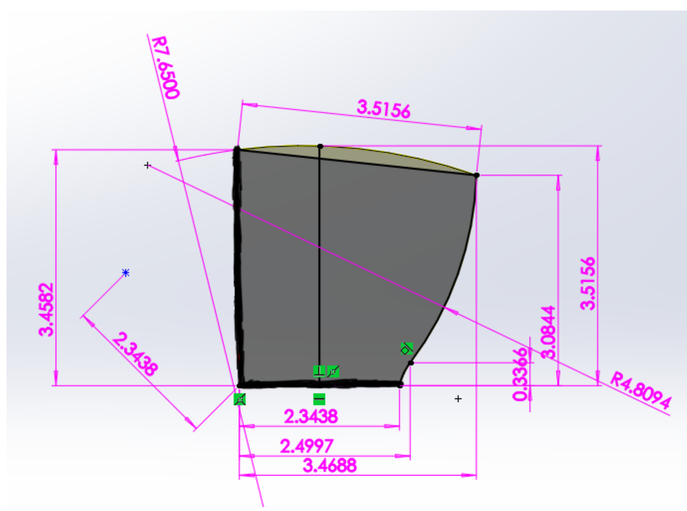

Figure 41. Edges of the palm base highlighted in black show datum points for dimensions

Design tables were used in order to scale the dimensions that should be scaled, and to fix the dimensions that should remain the same. Fixed dimensions consist of screw and mounting holes, shell thickness, hand thickness, and certain angles within the hand. These dimensions remain constant while the other dimensions are multiplied by a scale factor using the design table. As the final design was created using RCB's hand dimensions, it was designated as the full adult size.

There are also 15/16 and 7/8 sizes available through the configuration table. Any other sizes or alterations to specific dimensions can be implemented by the customer by accessing the table.

	D1@PB Sketch	D2@PB Sketch	D3@PB Sketch	D5@PB Sketch
Default	2.5	3.75	3.75	2.5
Fifteen Sixteenths	2.3	3.52	3.52	2.3
Seven Eighths	2.2	3.28	3.28	2.2

Table 1. Design table taken from Solidworks

It is important to note that if the hand is to be scaled any smaller than 7/8, smaller components will be required to fit within the model, such as smaller motors. The wrist cannot be scaled at all without replacing the servo motor that articulates it, as a smaller sized servo would be required for a smaller scale.

vii. Material Selection

One of the most common 3D printable plastics is polyacidic acid (PLA) [16]. However, as 3D printer manufacturers improve their printers, better materials are now available for printing as the hot ends that extrude the plastic are capable of reaching higher temperatures. Of these plastics are PETG and TPU [17]. With a tensile strength of 53.08 MPa, PETG has higher intera-slice bonding than PLA, which has a tensile strength of 49.98 MPa. Additionally, PETG is more chemically stable, has higher impact strength, more resistant to shock loading, and has a higher hardness than PLA [8]. However, PLA produces higher cosmetic quality products due to the lower hardness, but is more environmentally friendly, and requires lower temperature to manufacture [19]. Thus, if a 3D printer is capable of printing with PETG, the prosthetic arm should be made of PETG, but if that is not feasible, PLA can still be used. However, the pressure sensor cover must use TPU as it has high ductility, good biocompatibility, and excellent abrasion resistance [20]. Thus, the pad of TPU will be capable of protecting the sensor while maintaining adequate force measurement while in use.

Prototype Details

i. Drawings

To define the prosthetic arm sub-assemblies and all the components within them, drawings with exploded views and a bill of materials were made. The drawings can be found in Appendix F. Since our 3D CAD models will be uploaded to Github for people to use and modify, fully dimensioned drawings were not made. Figure 42 shows the lone drawing with dimensions, which provides a few overall dimensions of the hand to show the scale of the final prototype. It is intended to match RCB's hand as closely as possible.

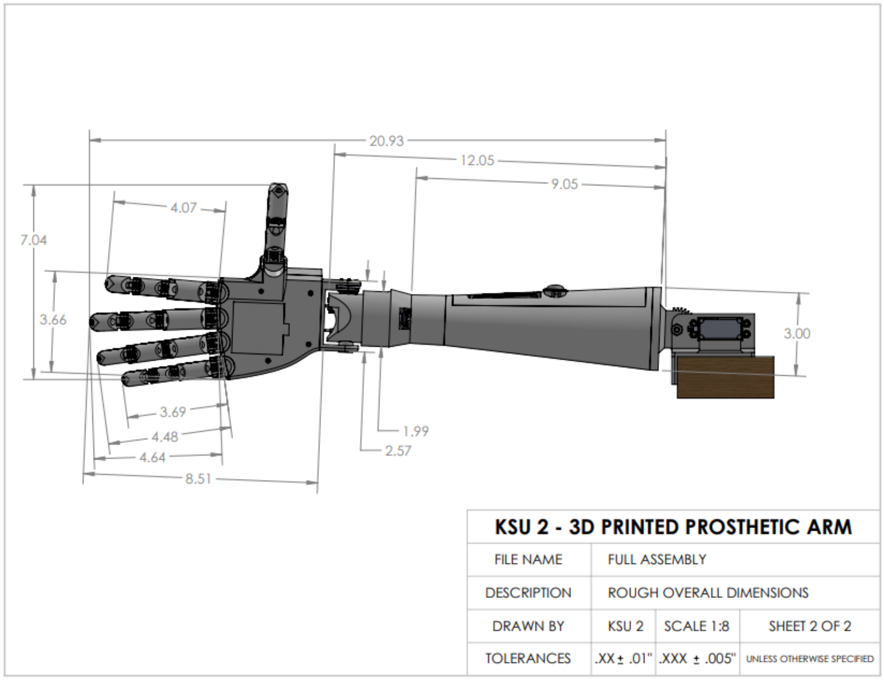

Figure 42. Rough Overall Dimensions of Full Assembly

ii. Overview of Analyses

Trial and error was the bulk of the analysis performed in this project, with every new prototype being preferred over the last. However, selection for purchased parts and design of the moving components were determined via simple calculations. For instance, the spool diameter was determined empirically by first measuring the required length of string to fully articulate a finger. Additionally, torsion spring selection was completed by computing required torque and comparing values to the servo motors that drove the fingers. Lastly, gear ratios to adequately increase torque from the elbow were calculated to ensure full functionality.

Trial and Error

Resultant of the current prototype being the first fully assembled and functioning prosthetic arm at KSU, much of the functionality and design aspects have never been considered. Thus, research papers only brought more questions than answers. For this reason, much of the design process was trial and error. For instance, to determine the proper articulation of the fingers, several iterations of fingers and joints as well as position on the palm were all considered and tested to determine feasibility.

Additionally, as ease of assembly was a major design focus, issues that arose during assembly would subsequently be fixed in the computer aided design

(CAD) model to ensure the consumer would not stumble into similar situations. One such example are the cutouts made in the wrist, each cutout was made to either allow for ease of assembly with screw and nuts or to better allow wires to be routed from the palm to the forearm.

However, some rudimentary calculations were computed as they would limit the amount of attempts required to achieve success. Of these calculations, the ones that aided in the final design are the selection of torsion springs, the determination of the servo spool diameter which drove the fingers, and the gear ratio required for the servo motor in the elbow to easily lift and lower the entire arm assembly, see Figure 43 for all the tested design revisions to create the final design.

Figure 43. Tested Iterations of Prototype Components

Selecting Torsion Springs

As the furthest required load from spring to moving object is the length of the middle finger at approximately 4.85 in. with a mass of 0.06 lbs. the required torque is estimated at 0.29 in.-lbs. Thus, with a required maximum torque determined, the next selection decision was the number of coils. Again looking at the middle finger, the gap removed to place the torsion spring is 0.30 in. wide. Therefore, a torsion spring with 180 degree left-hand wound, 0.224 in. outer diameter, and seven wounds were selected. With a torque of 0.405 in.-lbs. and thicker diameter, these torsion springs are slightly over the required specifications but are still well under the torque of the MG90s servo motors selected to drive the fingers, which have a torque of approximately 1.56 in.-lbs, see Appendix B, Figure B1 for more detailed specifications of the MG90s servo motors [7].

Servo Spool Diameter

With much of the range of motion of the fingers into the palm being dependent on the curling of the fingers, the distance of the string required to fully curl the finger must first be determined for the longest finger in order to compute the diameter of the spool placed on the motors driving the fingers. Given the dimensions of RCB, the middle finger was used as the datum for the largest phalange. Thus, to determine the distance traveled, a piece of string was fed through an assembled middle finger and a mark was placed on the string. Next, the string was pulled until the finger was fully curled with a new mark placed in the same location with respect to the finger as the previous. The distance between the two marks were then measured to determine the necessary size of the spool. As the max distance for the string to travel was determined empirically to be approximately 1.10 in., a spool diameter was then calculated by assuming the circumference of the spool was double the required distance traveled as the servo motors are only capable of traveling 180°. From this, the diameter was then calculated as 0.7 in., with a small grove routed through the spool to ensure the string followed the correct path.

Gear Ratio Selection:

A simple free body diagram (FBD is shown in Figure 43 that represents the center of mass of the whole arm being 16.5 inches away from the axis of rotation from the elbow.

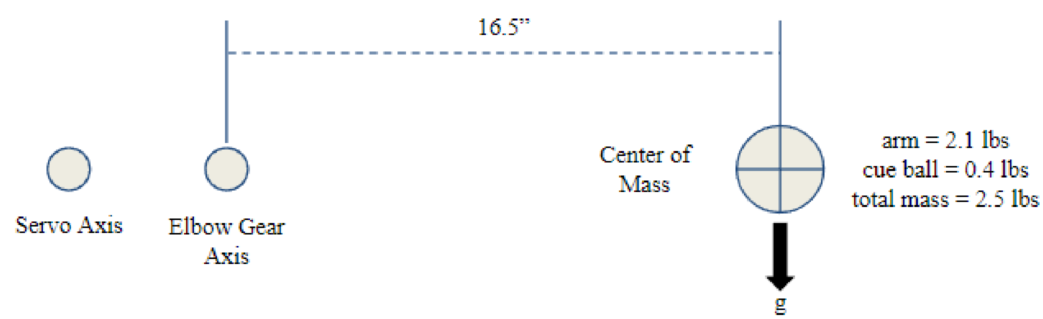

Figure 43. FBD of Elbow

The torque applied by the arm onto the elbow gear axis is the following:

$$\tau_{arm} = Force \cdot Distance$$

$$\tau_{arm} = 2.5\ lb\ \cdot 16.5\ in$$

$$\tau_{arm} = 41.25\ lb \cdot in$$

The servo to be used in the elbow has a max torque rating of 35 kg.-cm., and a 32 kg.-cm. rating when 6V is applied. The 32 kg.-cm. value will be used for the purposes of this analysis.

$$\tau_{servo} = (32\ kg \cdot cm) \cdot 0.86796\ \frac{lb \cdot in}{kg \cdot cm}$$

$$\tau_{servo} = 27.77\ lb \cdot in$$

$$Minimum\ Mechanical\ Advantage\ Needed\text{:}\ \frac{41.25\ lb \cdot in}{27.77\ lb \cdot in} = 1.482$$

Therefore, any gear ratio chosen will have to be greater than 1.482. The equation to relate torque to gear radius is the following:

$$\frac{\tau_{out}}{\tau_{in}} = \frac{d_{out}}{d_{in}}$$

$$\tau_{out} = \frac{d_{out}}{d_{in}} \cdot \tau_{in}$$

To achieve a mechanical advantage with the servo, the input gear from the servo must be smaller in diameter than the output gear that is attached to the elbow of the arm. For the factor of safety to be larger than 1, torque (arm) < torque (out) must be satisfied. To find an acceptable ratio of diameters, trial and error will be used with the calculations.

Attempt 1: $\tau_{out} = \frac{1\ in}{0.75\ in} \cdot 27.77\ lb \cdot in = 37.03\ lb \cdot in$

$\tau_{arm} > \tau_{out}$ so, this size won't work.

Attempt 2: $\tau_{out} = \frac{1.35\ in}{0.75\ in} \cdot 27.77\ lb \cdot in = 50\ lb \cdot in$

$\tau_{arm} < \tau_{out}$ therefore, this gear size can be chosen.

$$\frac{d_{out}}{d_{in}} = 1.8$$

$$\frac{n_{out}}{n_{in}} = \frac{36\ teeth}{21\ teeth} = 1.714$$

Since the gear teeth spacing isn't equal (0.012 in. compared to 0.018 in.), the ratio of teeth is the driving factor of gear ratio as opposed to diameter ratio. Figure 44 illustrates the final gear selection.

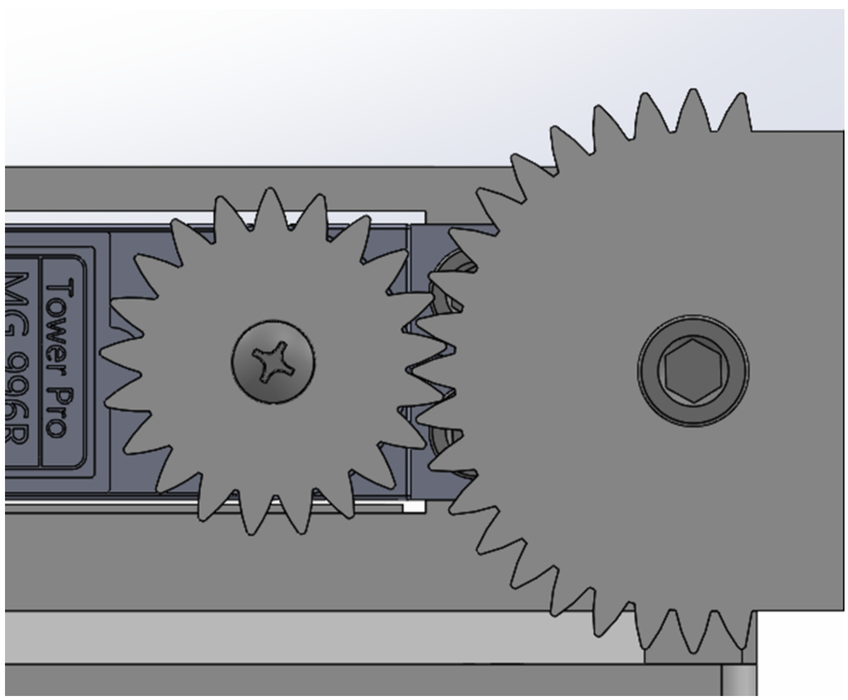

Figure 44. 21 Tooth Input Gear and 36 Tooth Output Gear

$$\tau_{out} = 1.714 \cdot 27.77\ lb \cdot in$$

$$\tau_{out} = 47.59\ lb \cdot in$$

$$\tau_{out} > \tau_{arm}$$

$$Factor\ of\ Safety = \frac{47.59}{41.25} = 1.154$$

Since the arm is designed to pick up a cue ball and an egg with the elbow joint fixed to a 2x4 piece of wood, this is acceptable. Additionally, the center of mass being at 16.5 in. away from the axis of the elbow gear is a conservative estimation.

Product Diagram

The final prototype only has one way that it is configured. Appendix F shows the connections of the printed components and how they connect overall through detailed drawings. For logic and circuit diagrams, appendix D provides additional information and figures for a more in depth look. Regarding the circuitry and electrical connections, these diagrams can be seen in the appendix in figure D1. This figure shows the connections between the Arduino, the force sensor, the bluetooth interface, the buck converter, and all of the servo motors that operate the prototype. To view the logic diagram for a full understanding of how to control the arm, figures D2 and D3 can be visited. These diagrams provide an in depth description of how the logic works with the Dabble controller, and how to access each mode to control the prosthetic accurately. In essence, the start button controls the movement of the fingers and thumb both individually and autonomously for the task of picking up an egg and a cueball. The select button is pressed in order to control the rotation and up and downward movement of the wrist, as well as the up and downward movement of the elbow components. Each button that is necessary for these operations is indicated in the aforementioned diagrams.

DFX Analyses

The prosthetic arm was designed for affordability, functionality, and accessibility. Throughout the design process, a priority was to utilize processes and components that were relatively affordable for the build and assembly of the arm. This was a main concern as any other option in the market can cost the consumer several thousands of dollars, which may not be financially feasible for them to attain. All of the mechanical and electrical components can be purchased from various mainstream distributors at a reasonable price, and at a much more affordable rate than other prosthetic arms that are currently available. The prototype was also designed to be fully functional in regards to the initial objectives (picking up an egg and cue ball) that were given by RCB. Vertical articulation, full rotational articulation, articulation of the fingers, as well as a pressure sensing mechanism are what was focused on regarding functionality. The final product meets all of these expectations. The final concept that this prototype was designed for was its accessibility. One of the project deliverables was to have the design files, instruction manuals, and any other relevant files and information easily available to anyone around the world. Therefore, all of the current design files can be easily accessed in .STL format for printing the parts and in a PDF format for the relevant information files. They will be available through an online file sharing service for anyone to access without any difficulties.

Applicable standards, specification, codes

The World Health Organization (WHO) outlines a plethora of guidelines and standards to follow for designing, sellings, and maintaining prosthetics. Although the current design of the prosthetic is rudimentary, with no consideration to the means of fastening the arm to a consumer, many of the other standards were utilized to drive the design of the prosthetic. These standards are as follows: the product should be functional, not endanger user safety, be durable, have the best possible cosmetic appearance, be relatively lightweight, and adaptable to the majority of users [21]. Of which, the current prosthetic is functional, with articulation in the fingers, wrist, and elbow. Next, as the prosthesis has all the electronics contained in a secure housing, the user should not be in danger of any electrical fires or other safety concerns. Additionally, the prosthesis is durable as it will be manufactured with PETG, which is very strong and chemically resistant, see Material Selection under the Conceptual Design Discussion section above. Lastly, although aesthetics were not the forefront of many design aspects, the end model is relatively human-life, with smaller options available, meeting the final standard the team believed were applicable to the current stage of the prosthetic arm development.

Costs (cost estimate and real costs)

Cost for the prosthetic arm will be under the assumption that the consumer who requires the prosthetic arm will be printing the parts themselves as the quote for the cost for a manufacturer to create these parts was difficult to acquire.

To create the arm, the customer must first assemble or obtain a 3D printer. Much of the parts were printed with a PRUSA MKIII I3, which can be found on PRUSA3D.com for about $899 [23]. However, a cheaper 3D printer can also be used so long as the hot end is capable of reaching 235 °C with a bed temperature of 85 °C to achieve optimal setting to print PETG. In conjunction, a spool of PETG filament will be required as all parts except the pressure sensor cover are printed from this material; a 1kg spool can be purchased from Amazon.com for $23.99 [23]. Additionally, a 200 g spool of TPU filament can be purchased from Amazon.com for $10.99 [24].

Next, for the fingers and palm, spider wire will be routed through all the fingers and tied to four MG90S 9g servo motors and 180° left-hand wound torsion springs will be placed between each finger segment. Spider wire can be purchased from Amazon.com for about $12.88 [25]. A pack of four MG90S 9g servo motors can also be purchased from Amazon.com for $14.98 [26]. Torsions springs can be purchased from McMaster.com for $6.51 for a pack of 6, thus for 14 torsion springs, 3 packs can be purchased for a total of $19.53 [7]. Additionally, if the user wishes to place a force sensor within the palm, a FSR01CE can be purchased from DigiKey.com for $11.23 [27]. Following this, the two MG996R servo motors in the wrist can be purchased from Amazon.com for $20.99 [28]. In tandem, the DS3235 35KG Coreless Stainless Steel Gear Waterproof Digital Servo Motor placed in the elbow for demonstration can also be purchased from Amazon.com for $29.99 [29]. The mounting screws for the entire assembly can then be purchased from McMaster.com for a total of $37.33 [30]. To assist in fastening the various screws, a HTM 128 Piece Screwdriver Toolkit can be purchased from Amazon.com for $24.99.

Lastly, the remaining electronics to be purchased are an Adruino Mega 2560 R3, a buck converter with adjustable voltage and amperage, and miscellaneous wires to connect all the electronics in the prosthetic arm. An Arduino Nano can be purchased from Amazon.com for $11.99 [31]. An adjustable buck converter can be purchased from Amazon.com as well for $13.99 [32]. Additionally, a Lithium Ion battery with over 6V and 2000 mAh should be purchased to power the arm, Amazon offers a plethora of options, batteries from Blomiky were used for this prototype. Lastly, two packs of various jumper wires can be purchased from Amazon.com for a total of $18.97 [33]. Thus, the total cost for the prosthetic arm is approximately $289.84 with many extra parts such as excess filament and screws remaining for maintenance and repair. However, this figure does not include the price of a 3D printer which could increase the cost by over $900 (see Table 2 for the itemized list of parts, quantity, and prices without the 3D printer).

Item	Quantity	Cost
1 kg Spool PETG Filament	1	$23.99
200 g Spool TPU Filament	1	$10.99
SpiderWire	1	$12.88
MG90S 9g Servo (4 pk)	1	$14.98
Torsion Spring (6 pk)	3	$19.53
Force Sensor	1	$11.23
MG996R (4 pk)	1	$20.99
DS3235 35 KG Servo	1	$29.99
Mount Screws (Various)	1	$37.33
Arduino Nano	1	$11.99

Adjustable Buck Converter	1	$13.99
7.4V 2000mAh LiPo Battery (2 pk)	1	$31.99
Jumper Wires (Various)	1	$18.97
HTM 128pc Screwdriver Toolkit	1	$24.99
	Total	$289.84

Table 2. Itemized Cost for the Prosthetic Arm

Clear proof that all specifications have been met

As discussed above, a complete set of SOLIDWORKS models with RCB's hand and arm dimensions have been created. In tandem, scalable parts have also been modeled using the SOLIDWORKS "Design Table" feature. Furthermore, the non-3D printed parts are all purchased from large distributors (Amazon, Digikey, and McMaster Carr). Additionally, with the assistance of a force sensor in the palm, the prototype was capable of lifting an egg and cue ball without dropping or breaking the objects as seen in Figure 45.

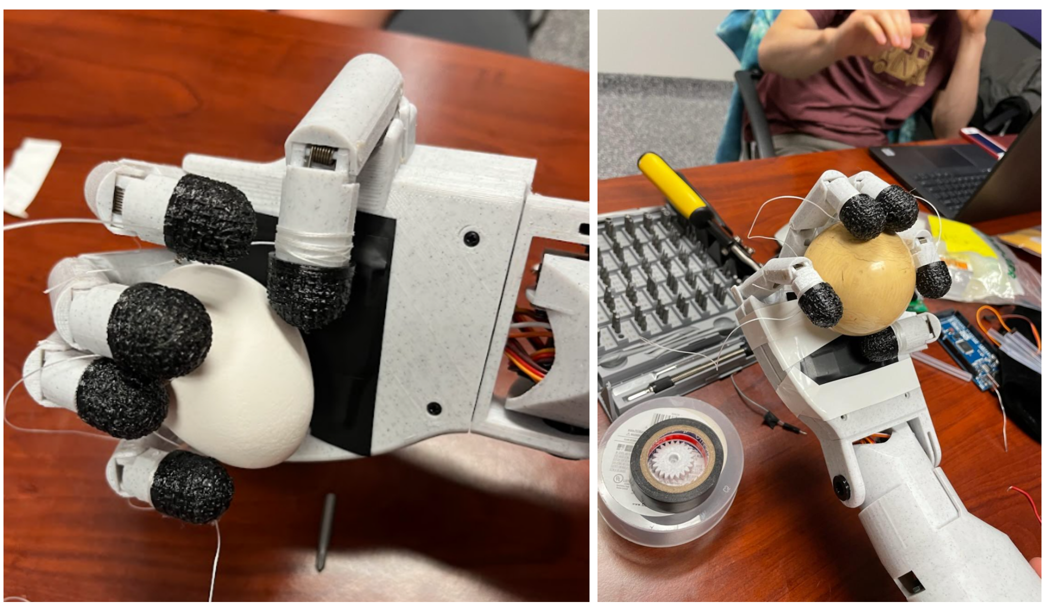

Figure 45. Prosthetic Arm Prototype Grasping an Egg and Cueball

Validation and Verification: Plan or Results

After continuous testing with the prototype prosthetic arm, all of the deliverables were met, but many still require additional development and refinement. To begin, the complete set of SOLIDWORKS models with respective STL files for the 3D printed components were created and uploaded to an online repository that can be found at:

https://github.com/ZhiJie88/Electromechanical-3D-Printed-Prosthetic-Arm-Initiative-SPRING-2023.

Also uploaded to this repository was all technical documentation, including a user manual. Additionally, all non 3D printed parts have been sourced from mass distributors and can be found in a text file in the repository. Culminating from these parts, a prototype was assembled that was capable of grasping an egg and cue ball. However, the grip is not consistent, meaning that some objects can only be gripped if approached at the correct angle. To fix this, shifting the attachment of the fingers to the palm could assist in range of motion to fully encompass the hand. Additionally, the arm is scalable with the only limiting factor being the footprint of the electronics and wire management. Control of the arm using the “Dabble” phone application proved to be successful and user-friendly to a degree. However, overall the arm is still difficult to assemble, requiring a plethora of drivers and understanding of the models to adequately assemble the prototype.

Bill of Materials

The bill of materials (BOM) was generated from the final assembly in the SOLIDWORKS model (Appendix G). It is divided between the three major assemblies of the prototype: palm, wrist, and elbow. Parts within each subassembly are named and a quantity is listed to show how many of each part are used, accompanied by a description of the part. It is important to note that there are some parts that are shared between the three subassemblies when interpreting the quantities of each part. For example, part “91249A046” has some quantities that are shared between the palm and the wrist, so some of those bolts are already accounted for in the previous assembly. The quantity solely pertains to the sub-assembly itself, not the quantity of the part overall.

Gantt Chart

At the beginning of the semester a Gantt Chart was created to lay out the preliminary steps of the project, as seen in Appendix H. Key timeline goals were established, including the following:

- Finalize the conceptual design by February 20th
- Build the first prototype by March 10th
- Build the second prototype by April 21st
- Build the third and final prototype by May 2th

The first prototype build was behind schedule. Much progress was made during Spring Break, and at the end of it the first prototype was complete on March 18th. This design, as seen in Figure 46, had minimal electronics, did not have an elbow, and featured many design flaws that limited assembly. Many of these problems were fixed with the completion of the 2nd prototype on April 19th, which can also be seen in Figure 46. It included a more complete electronics package along with a forearm and elbow design, but assembly issues persisted. The elbow design of the 2nd prototype did not have sufficient torque to lift and control the entire arm.

In the final weeks of the project a redesign to the elbow gear system was made. These updates were documented in the “Forearm and Elbow” section of the Conceptual Design Discussion in this report. The final prototype was completed on May 2nd for the Final Design Review Presentation on May 3rd. The final prototype fixed many of the main concerns pertaining to assembly, in addition to including a simplified electronics package and an elbow that is capable of lifting the whole arm.

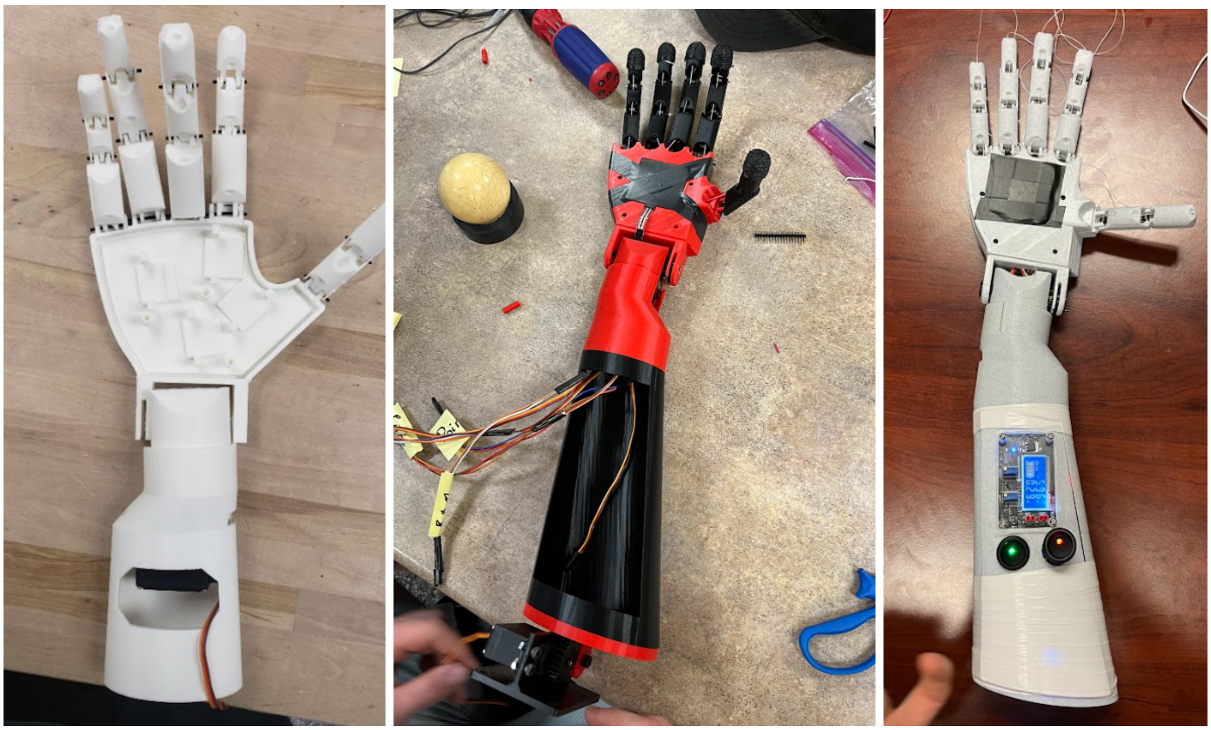

Figure 46. From Left to Right are the First Prototype from March 18. Second Prototype from April 19 and the Final Prototype From May 2

Ethical and Safety Considerations

A concern regarding prosthetics is their accessibility for individuals who require them to accomplish everyday tasks. Most prosthetics cost thousands of dollars for individuals who do not have health insurance, and “are still accessible only to a small percentage of those who could benefit from them” [34]. The goal of the design is to make a prosthetic arm that can be easily fabricated through 3D printing, while also keeping the price relatively low. This is a large concern for prosthetics that undergo wear and tear over time. Furthermore, children rapidly grow into adulthood and need larger devices as they mature, which leads to high financial strain of constantly replacing arms that fit better. For that reason, the design will be easily scalable for individuals who need a replacement without having to worry about astronomical costs.

The outer shell of the arm protects the interior components from impact from foreign objects and everyday use. There is a small risk of minor injury from interacting with the mechanical and electrical components if they are not properly managed, including pinching and minor electrical shock. To avoid this, the team properly sealed these components in their designated compartments, and designed it so that they can only be accessed with the proper tools. The product has an owner's manual that provides details on how to properly care for the prosthetic and a full description of its functionalities. It also includes a recommended lifespan for several parts, such as the battery and the motors, to avoid any malfunctions that could lead to injury to the user.

Global, Economic, Environmental, and Societal Considerations

This design has the potential to reach anyone around the world that is in need of a prosthetic arm. The free design is available to all through open sources online so that anyone in need can either print and assemble the parts themselves or seek a company to do it for them at a low cost. This design promotes a worldwide increase in sales of the components necessary for assembly, such as plastic filament, motors, and battery, which ultimately boosts the economy. This also has the potential to introduce new competition in the market for prosthetics, encouraging higher end prosthetic arms to lower their prices in order to compete with the more affordable models.

The largest environmental consideration is the disposal of the product and its individual components. The prosthetic arm is mostly constructed of PETG plastic for the exterior body and for the joints in the fingers. PETG has high chemical and impact resistance, good chemical and mechanical stability, and is also recyclable [35]. The battery and other electrical components can also be properly disposed of in designated battery disposal drop offs.

The accessibility of 3D printers has increased dramatically over the last decade, which is why this design was made for additive manufacturing. Low-income families will have a much easier time finding a 3D printer to fabricate the design than they will accumulating the funds for a prosthetic that costs them thousands of dollars. Many schools and communities now have easily accessible makerspaces that can be utilized to build this design for little to no cost.

Conclusions and Recommendations

At the conclusion of this project, there are many parts that can and should be improved. For customers who would like a more lifelike prosthetic, there are many areas of this prosthetic that could be modified to appear more organic. Areas such as where the wrist joins the forearm and the fingers could be considered for remodel. Printing filament could also be selectively chosen to match the skin tone of the customer. Ideally the controlling mechanism for future adaptations moves away from a device that requires a user to press buttons, specifically considering the fact that customers who are in need of two prosthetics would struggle with the current controller. Alternative methods include myoelectricity, "magnetomicrometry", and Brain-Computer Interfaces. This product also currently leaves few choices of size for the customer to pick from. Ideally this prosthetic would be easier for the customer to customize to their personal length and width for each component on the arm. Lastly, the elbow attached to this prototype was purely designed to demonstrate the capabilities of the prototype. In future iterations this product would have a stronger and more presentable elbow that has a comfortable fitting to the user's residual limb.

Acknowledgements

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Appendix A - RCB Hand and Forearm Dimensions

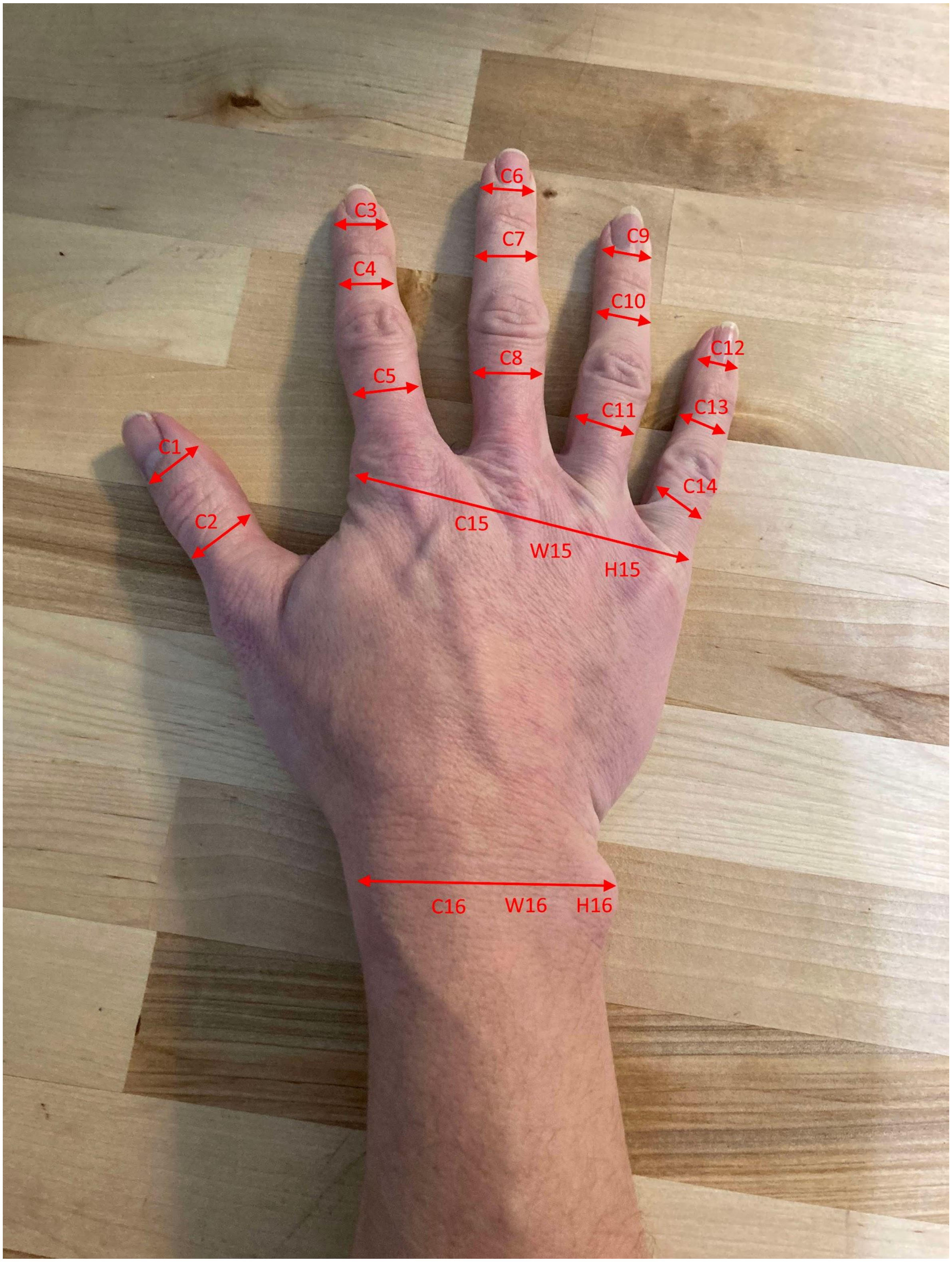


Figure A1. RCB Right Hand Width Measurements

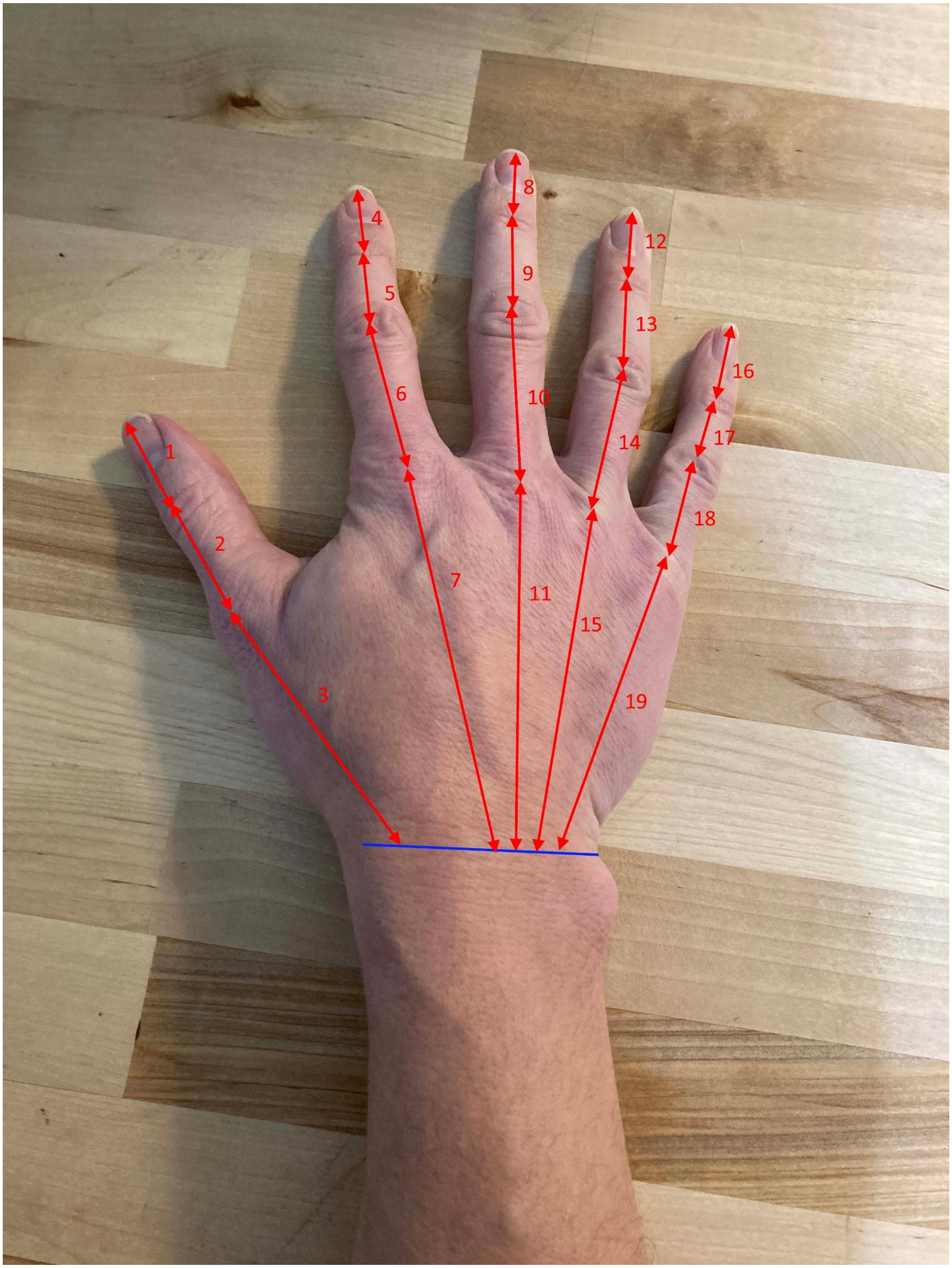


Figure A2. RCB Right Hand Length Measurements

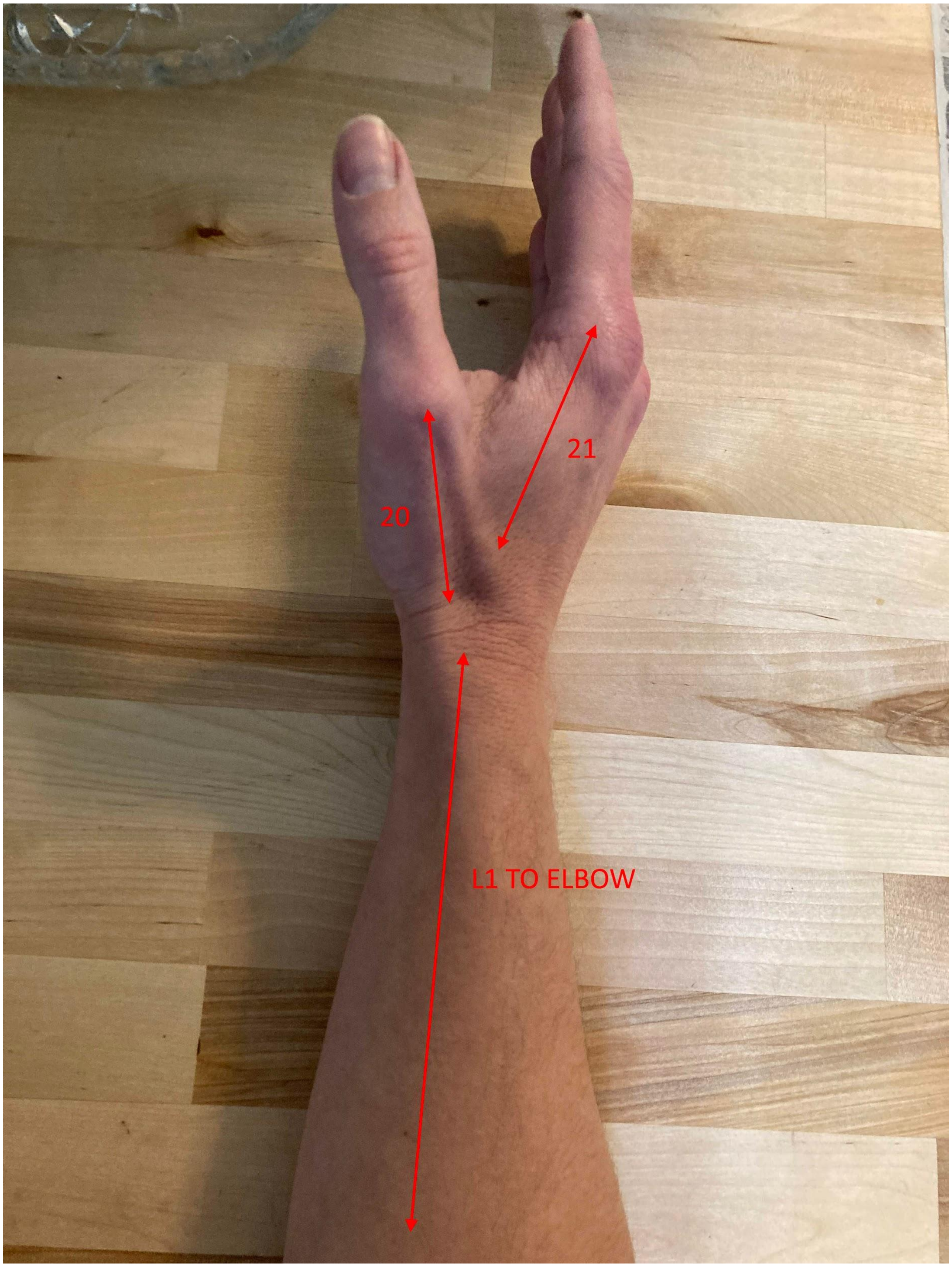


Figure A3. RCB Right Wrist and Forearm Measurements

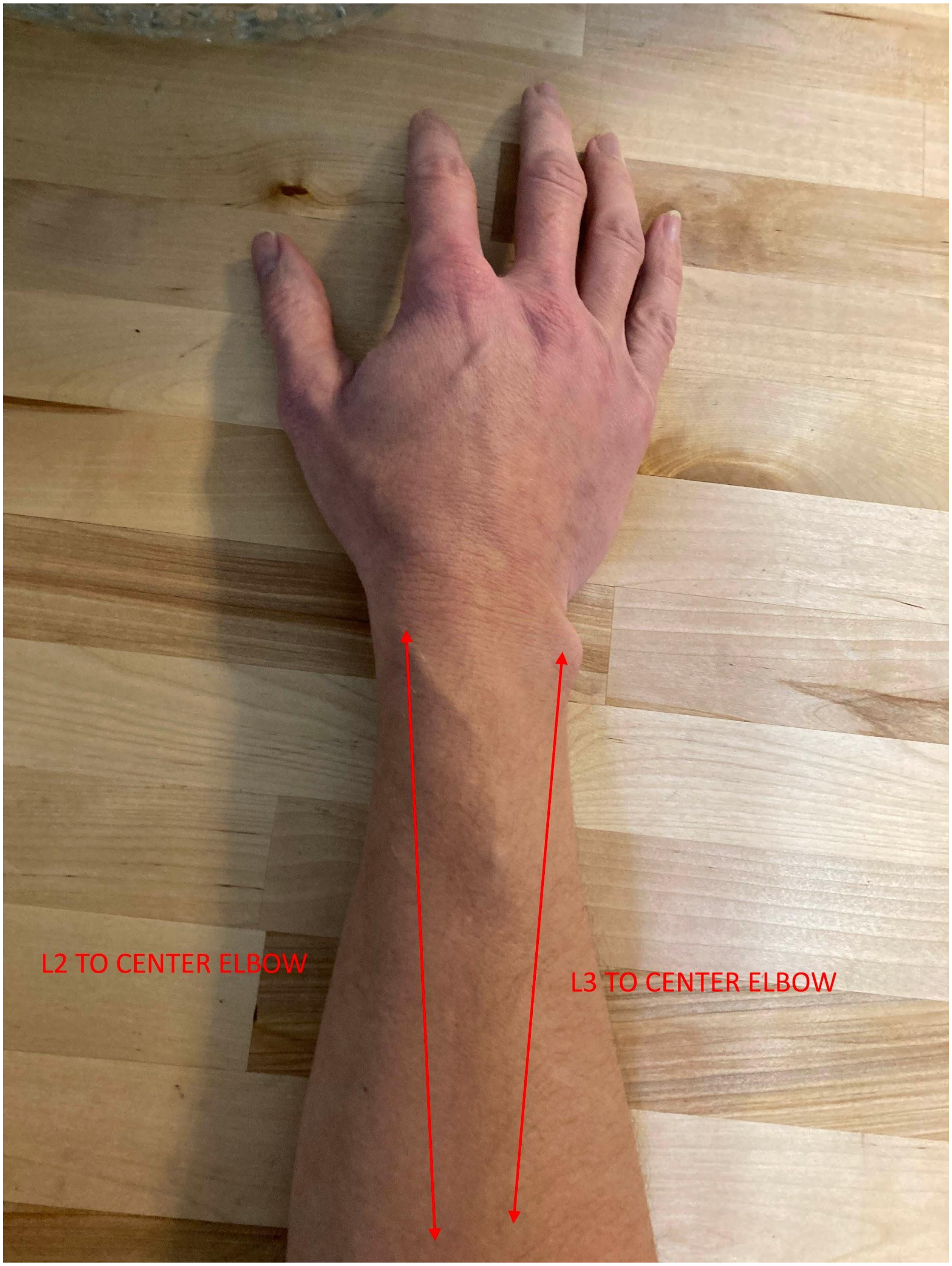


Figure A4. RCB Right Forearm Measurements

RCB Hand and Forearm Dimensions from Images Above	
Reference Name From Images	**Dimension (in)**
1	1.375
2	1.625
3	3.250
4	1.000
5	1.250
6	2.125
7	4.250
8	1.125
9	1.500
10	2.375
11	3.750
12	1.125
13	1.500
14	2.375
15	3.250
16	1.000
17	1.000
18	2.000
19	3.250
20	2.500
21	2.500
C1	2.125
C2	2.375
C3	1.875
C4	2.250
C5	2.750
C6	2.000
C7	2.250
C8	2.500
C9	1.625
C10	2.000
C11	2.500
C12	1.625
C13	1.750
C14	2.250
C15	8.500
C16	6.500
W15	3.750
W16	2.500
H15	1.000
H16	1.375
L1	11.000
L2	11.000
L3	10.500

Table A2. RCB Hand and Forearm Dimensions

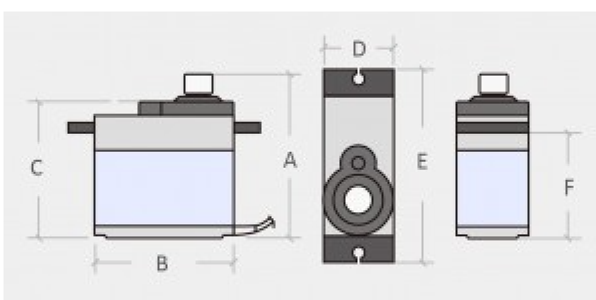
Appendix B - Quality Function Deployment (QFD)

Requirement	Kano Classification	Customer Desired Rank	KSU Repository Arm	KSU Undergrad Prototype	*open bionics* Hero Arm	Team 2 Prototype
Cost	basic	5 (good)	5 (good)	5 (good)	3 (acceptable)	5 (good)
Reliability	basic	5 (good)	1 (poor)	5 (good)	5 (good)	3 (acceptable)
Durability	performance	3 (acceptable)	1 (poor)	5 (good)	5 (good)	3 (acceptable)
Strength	performance	3 (acceptable)	1 (poor)	3 (acceptable)	5 (good)	1 (poor)
Scalability	performance	3 (acceptable)	1 (poor)	1 (poor)	5 (good)	3 (acceptable)
Weight	performance	5 (good)	3 (acceptable)	3 (acceptable)	5 (good)	5 (good)
Wrist Articulation (Up and Down)	basic	5 (good)	1 (poor)	1 (poor)	3 (acceptable)	5 (good)
Wrist Articulation (Side to Side)	performance	1 (poor)	1 (poor)	1 (poor)	1 (poor)	1 (poor)
Wrist Articulation (Rotational)	basic	5 (good)	1 (poor)	1 (poor)	5 (good)	5 (good)
Ease of Assembly	basic	5 (good)	1 (poor)	3 (acceptable)	5 (good)	3 (acceptable)
Number of Pieces to Assemble	performance	3 (acceptable)	5 (good)	5 (good)	5 (good)	1 (poor)
Ease of Repair	basic	5 (good)	5 (good)	3 (acceptable)	1 (poor)	3 (acceptable)
Rechargeable Batteries	performance	3 (acceptable)	1 (poor)	1 (poor)	5 (good)	5 (good)
Aesthetics (Resemblance)	excitement	3 (acceptable)	1 (poor)	5 (good)	5 (good)	3 (acceptable)
Noise Above ambient	excitement	1 (poor)	3 (acceptable)	3 (acceptable)	5 (good)	3 (acceptable)
Pressure Sensing	performance	5 (good)	1 (poor)	1 (poor)	5 (good)	3 (acceptable)
Effect of Materials on Consumer	basic	5 (good)	5 (good)	5 (good)	5 (good)	5 (good)
Effect of Materials on Environment	basic	3 (acceptable)	3 (acceptable)	3 (acceptable)	3 (acceptable)	3 (acceptable)
Waterproof	excitement	1 (poor)	1 (poor)	1 (poor)	1 (poor)	1 (poor)
Totals		**69**	**45**	**55**	77	**61**

Appendix C - Datasheets for Components in Prototype Prosthetic Arm

TECHNICAL SPECIFICATIONS

Motor Model		Generic MG90S (China)
Drive Type		Analog
Degree Rotation		180° (±15°)
Operating Ratings		
	Voltage	4.8-6 VDC (5V Typical)
	Current (idle)	10mA (typical)
	Current (typical during movement)	120-250mA
	Current (stall)	700mA (measured)
	Stall Torque	2.2kg-cm (per spec)
	Speed	0.12s / 60 degree (varies with VDC)
Dimensions		
	Cable Length	24cm (9.5″)
	Motor Housing L x W x H	23 x 12 x 26mm (0.9 x0 .5 x 1″)
	Motor Height (w/ shaft)	32mm (1.26″)
	Motor Housing Width with Mounting Ears	32mm (1.26″)



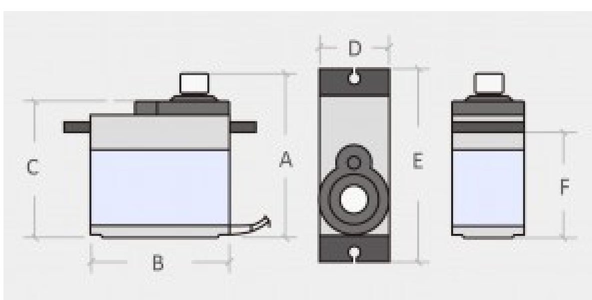
PRODUCT CONFIGURE TABLE

Weight(g)	13.4
Torque(kg)(4.8v)	1.8
Speed(sec/60deg)	0.1
A(mm)	32.5
B(mm)	22.8
C(mm)	28.4
D(mm)	12.4
E(mm)	32.1
F(mm)	18.5

Figure C1. MG90s Servo Motor Specifications and Footprint

TECHNICAL SPECIFICATIONS

Motor Model		Generic MG996 (China)
Drive Type		Analog
Degree Rotation		180° (±10°)
Operating Ratings		
	Voltage	4.8-6VDC (5V Typical)
	Current (idle)	10mA (typical)
	Current (typical during movement)	170-400mA
	Current (stall)	1.3 – 1.5A (measured)
	Stall Torque	13kg-cm (typical)
	Speed	0.2s / 60 degree (varies with VDC)
Dimensions		
	Cable Length	28cm (11″)
	Motor Housing L x W x H	40.9 x 20 x 39mm (1.6 x 0 .79 x 1.53″)
	Motor Height (w/ shaft)	45mm (1.77″)
	Motor Housing Width with Mounting Ears	54mm (2.13″)



PRODUCT CONFIGURE TABLE

Weight(g)	55
Torque(kg)(4.8v)	9.4
Speed(sec/60deg)	0.17
A(mm)	42.7
B(mm)	40.9
C(mm0	37
D(mm)	20
E(mm)	54
F(mm)	26.8

Figure C2. MG996R Servo Motor Specifications and Footprint

SERIES SPECIFICATIONS

Series	Active area	Thickness (inc. 0.05mm adhesive)	Sensor overall width	Sensor overall length	Tail length	Tail width
FSR01	39.70 x 39.70mm	0.375mm	43.69 x 43.69mm	83.09mm	39.40mm	7.62mm
FSR02	604.60 x 10.20mm	0.375mm	15.20mm	622.30mm	12.70mm	7.60mm
FSR03	ø25.42mm	0.425mm	30.50mm	69.00mm	38.00mm	7.62mm
FSR04	ø5.60mm	0.325mm	7.62mm	15.80mm	9.00mm	6.35mm
FSR05	ø5.60mm	0.325mm	7.62mm	38.10mm	30.00mm	6.35mm
FSR06	ø14.70mm	0.375mm	18.00mm	25.00mm	9.00mm	7.62mm
FSR07	ø14.70mm	0.375mm	18.00mm	56.34mm	38.00mm	7.62mm

CHARACTERISTICS

Characteristic	Description	FSR01	FSR02	FSR03	FSR04	FSR05	FSR06	FSR07
Actuation force	Force to reach 10MΩ, Average of 100 samples	< 20g	< 20g	< 10g	<20g	<30g	<15g	<15g
Force range	linear region of log/log, Higher forces can be achieved with custom sensor and actuation methods	All: Up to 5kg						
Long term drift	1kg for 48hrs, Per log time	< 2%	< 1%	< 1%	< 2%	< 2%	1%	1%
Single part repeatability	100 actuations of 1kg, 1 standard deviation/mean	All: 2%						
Part to part repeatability	100 sensors same batch, 1 standard deviation/mean	All: ±4%						
Low temp. storage	−20°C for 250hrs, Avg. change in res. of 5 sensors	8%	7%	7%	8%	8%	7%	7%
High temp. storage	+85°C for 250hrs, Avg. change in res. of 5 sensors	4%	3%	3%	4%	4%	3%	3%
High humidity storage	+85°C/85%RH for 250hrs, Avg. change in res. of 5 sensors	8%	12%	8%	8%	8%	12%	12%
Lifecycle durability	(10M) 1kg force at 3Hz, Avg. change in res. of 4 sensors	17%	12%	3%	7%	7%	3%	3%
Hysteresis	100 actuations of 1kg, Avg. change in res. of 100 samples	All: 5%						
Operational temp. range	100 cycles at 0.5kg	All: −20 to +85°C						

Note: All values typical, and quoted at 10N applied force unless otherwise stated. Force dependant on actuation interface, mechanics, touch location, and measurement electronics.

	FSR01-03	FSR04	FSR05	FSR06	FSR07
Mode	Shunt	Shunt	Shunt	Shunt	Shunt
Trace pitch	0.25mm	0.50mm	0.50mm	0.50mm	0.50mm
Spacer height	0.125mm	0.125mm	0.125mm	0.125mm	0.125mm
Trace width	0.25mm	0.25mm	0.25mm	0.25mm	0.25mm

Figure C3. FSR01CE Specification Sheet

No.	Operating Voltage	5V	6V	7.4V
3-1	Idle current (at stopped)	5mA	5mA	5mA
3-2	Operating speed (at no load)	0.13 sec/60°	0.12 sec/60°	0.11sec/60°
3-3	Stall torque (at locked)	29 kg-cm	32 kg-cm	35 kg-cm
3-4	Stall current (at locked)	1.9A	2.1 A	2.3A

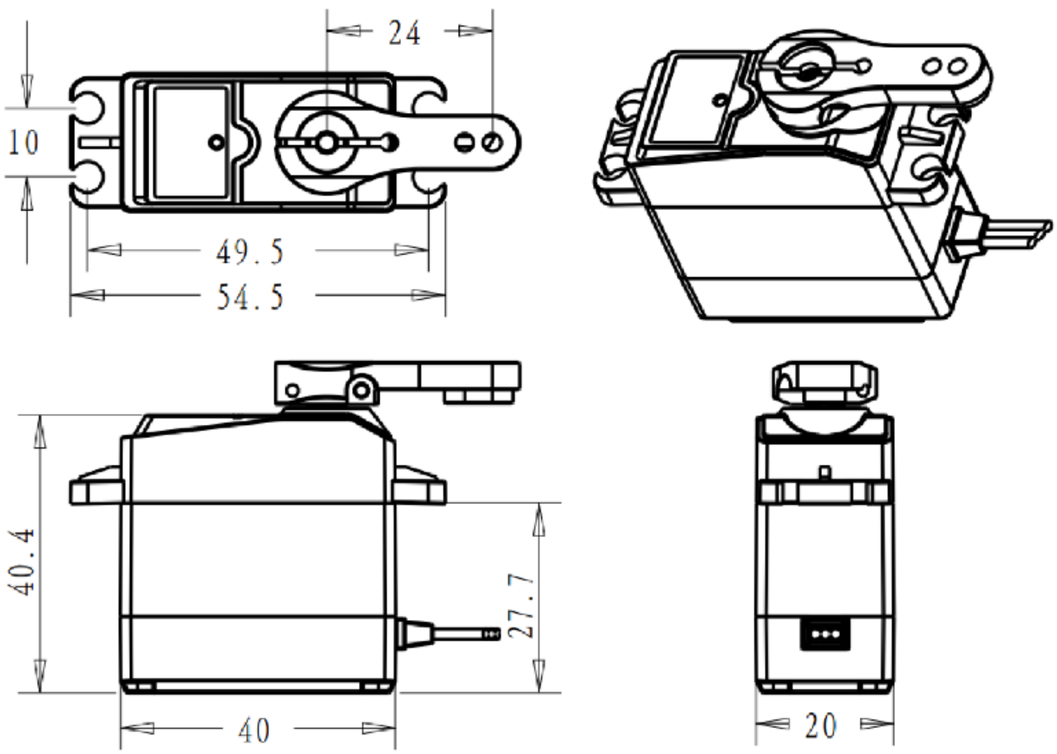


Figure C4. DS Servo 35kg Servo Motor Specifications and Footprint

Appendix D - Circuit, Logic, and Movement Diagram

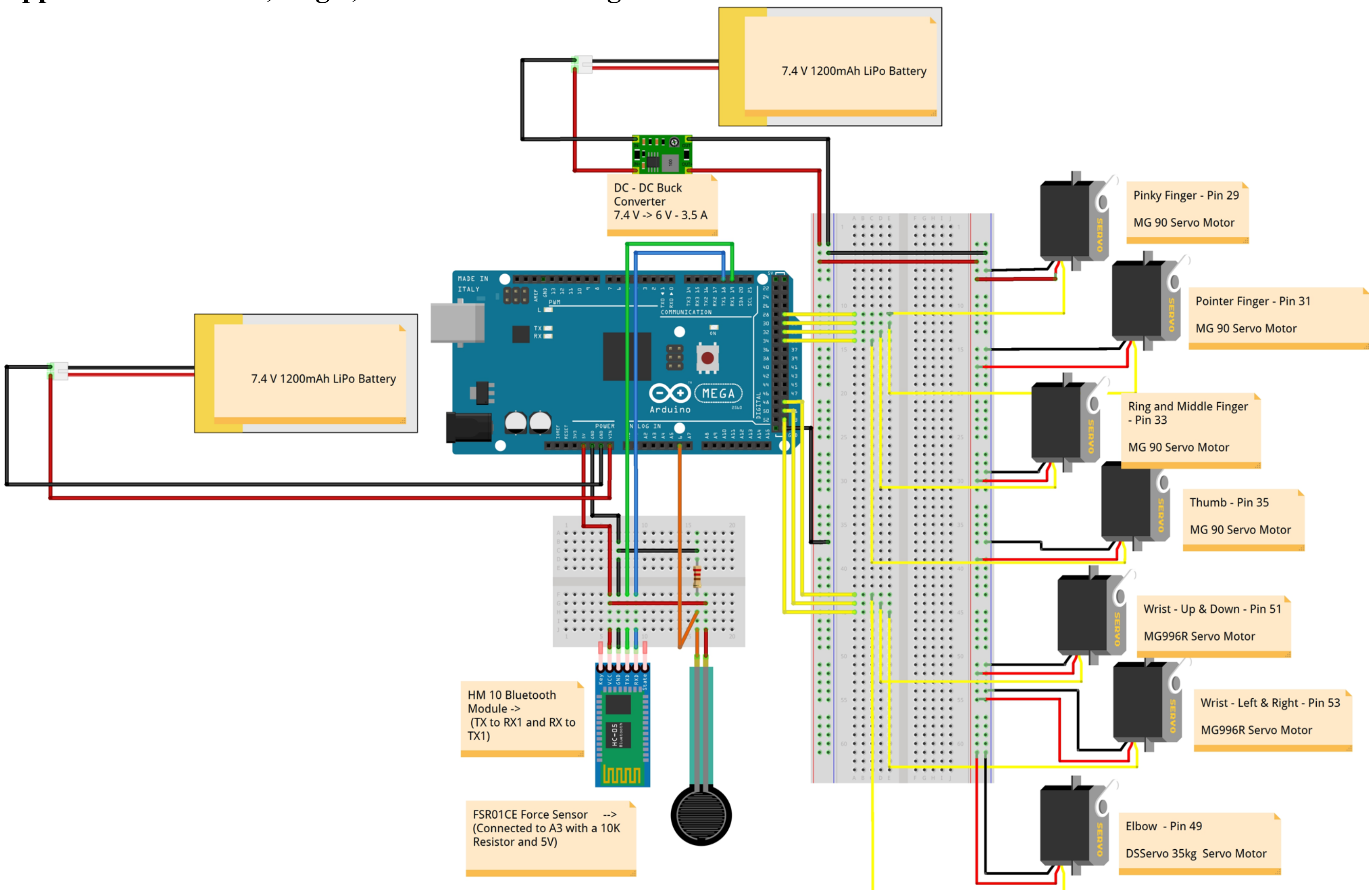


Figure D1. Prosthetic Arm Circuit Diagram

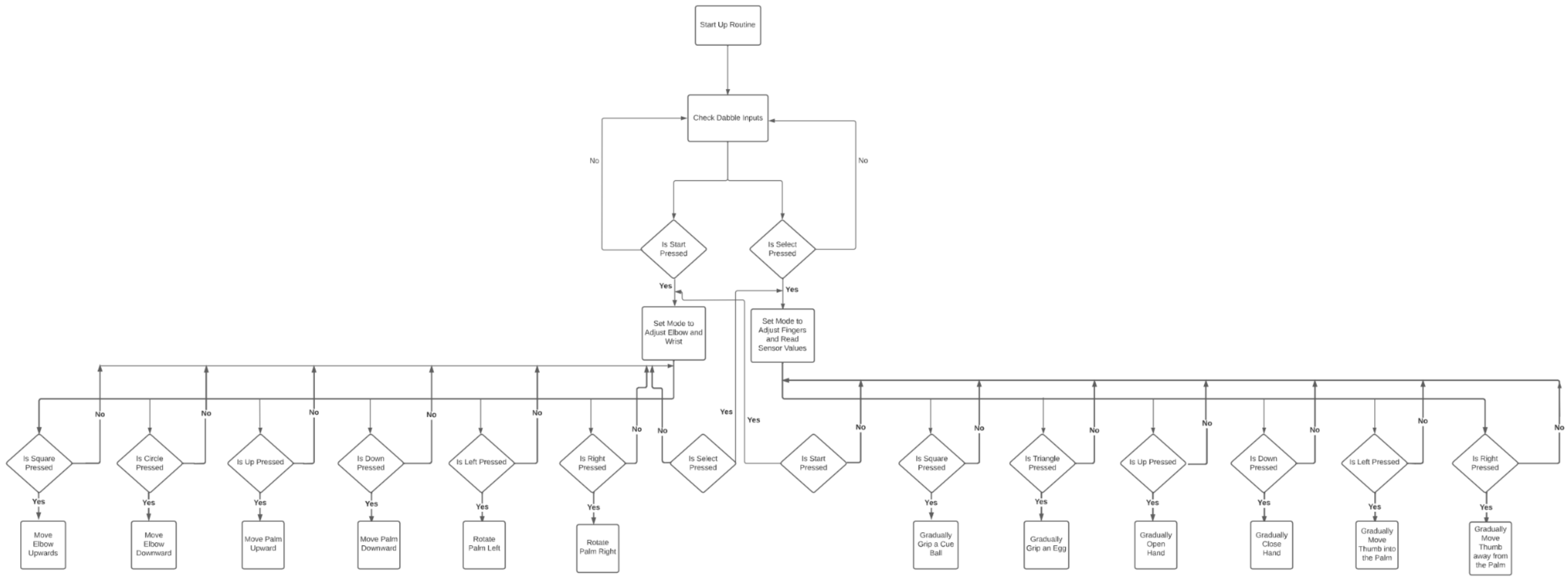


Figure D2. Prosthetic Arm Logic Diagram

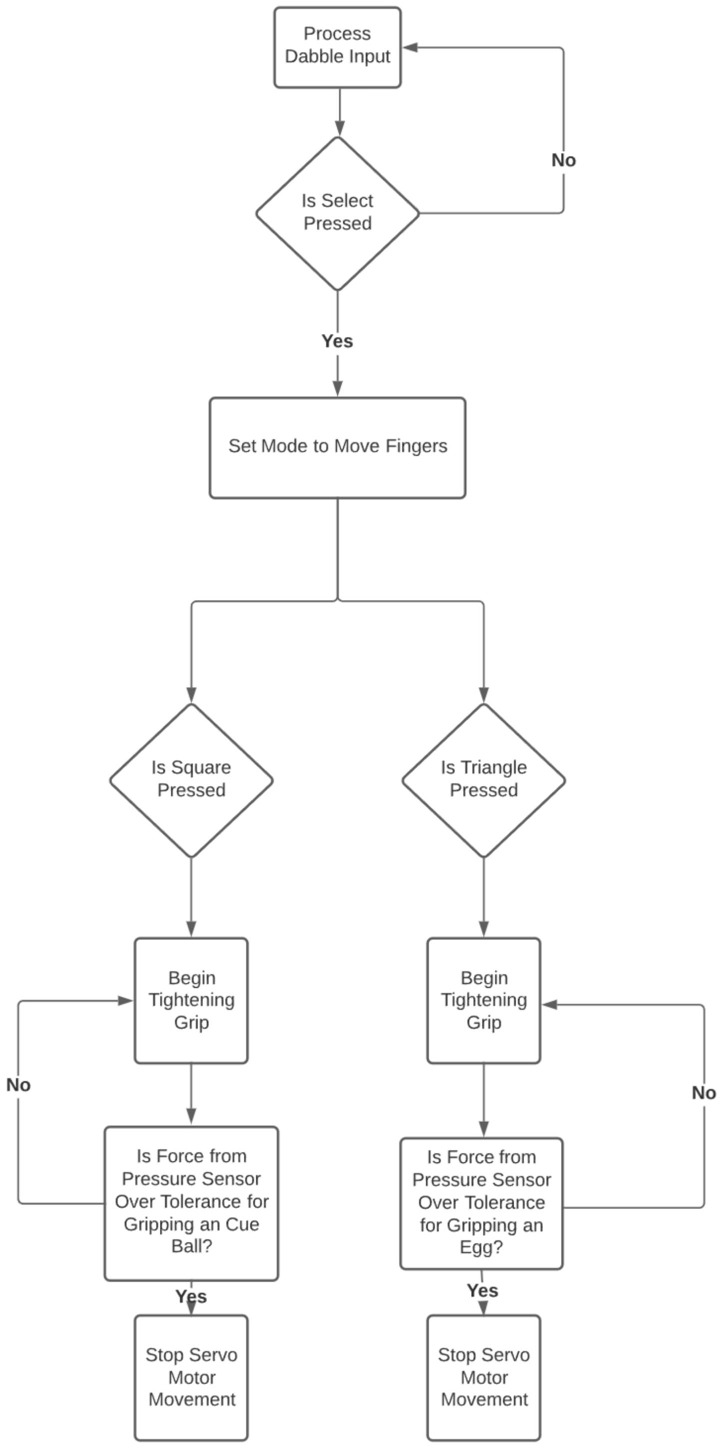


Figure D3. Prosthetic Arm Movement Diagram

Appendix E - Program to Control Prosthetic Arm

```
// Set reference and variables for dabble bluetooth interface
#define CUSTOM_SETTINGS
#define INCLUDE_GAMEPAD_MODULE
#include <Dabble.h>

//Set reference to servo library
#include <Servo.h>

//Variables to reference the servo library
Servo pointer;
Servo ringmiddle;
Servo thumb;
Servo pinky;
Servo wristUD;
Servo wristLR;
Servo elbow;
Servo elbow2;

//State Denoter
uint8_t mode = 0;

//Pins for MG90s servo motors in the hand
const uint8_t pointerPin = 31;
const uint8_t ringmiddlePin = 33;
const uint8_t pinkyPin = 29;
const uint8_t thumbPin = 35;

//Pins for MG996R servo motors in the wrist
const uint8_t wristUDPin = 53;
const uint8_t wristLRPin = 51;

//Pin for DS3235 35KG servo motor in the elbow
const uint8_t elbowPin = 49;

//Variable representing direction and current servo positions
uint8_t pPos;
uint8_t pinkyPos;
uint8_t mPos;
uint8_t tPos;

//LED Pins
const uint8_t redPin = A1;
const uint8_t greenPin = A0;
const uint8_t bluePin = A2;
```

```
//Pressure sensor pin
const uint8_t fsrPin = A3;

bool upButState = false;
bool downButState = false;
bool leftButState = false;
bool rightButState = false;
bool startButState = false;
bool selectButState = false;
bool triangleButState = false;
bool squareButState = false;
bool crossButState = false;
bool circleButState = false;
bool stopGrip = false;
bool stopExtension = false;
//Inital startup for Arduino
void setup()
{
  //Defines a baud rate to communicate between the Serial Monitor and the Arduino to aid in
debugging
  Serial.begin(115200);

  //Defines baud rate to communicate with the HM-10 Bluetooth Module to communicate with
the Dabble App Interface
  Dabble.begin(9600);

  //Initialize servos for the fingers, wrist, and elbows
  initFingers();
  initWrist();
  initElbow();

  //Initialize pin for sensor
  initSensor();

  //Initialize pins RGB lighting
  initRGB();
}

//Arduino main looping function, repeated until Arduino is powered off
void loop()
{
  //Allows the Arduino to process information from the Dabble App
  Dabble.processInput();

  //Set mode to adjust wrist and elbow
```

```
  if (GamePad.isSelectPressed())
  {
   mode = 1;
  }

  //Set mode to adjust hand
  if (GamePad.isStartPressed())
  {
   mode = 2;
  }

  //Calls function to perform functionality test for the hand
  if (mode == 0)
  {
   RGB(0, 255, 0);
   rigorMortis();
  }

  //Calls functions to control wrist and elbow
  else if (mode == 1)
  {
   RGB(255, 0, 0);
   adjustWristElbow();
  }

  //Calls functions to control fingers
  else if (mode == 2)
  {
   RGB(0, 0, 255);
   adjustHand();
  }

  //Reads values from pressure / force sensor
  uint16_t fsrVal = analogRead(fsrPin);
  Serial.print("FSR VAL:");
  Serial.println(fsrVal);
}

// Initialize all the servos for each finger, setting initial positions accordingly
void initFingers()
{
  pointer.attach(pointerPin);
  ringmiddle.attach(ringmiddlePin);
  thumb.attach(thumbPin);
  pinky.attach(pinkyPin);
  pointer.write(180);
```

```
  delay(20);
  ringmiddle.write(0); // The servo controlling the ring and middle finger is placed in the opposite orientation compared to the other finger servos
  delay(20);
  thumb.write(180);
  delay(20);
  pinky.write(180);
  delay(20); // Small delay to ensure the power supply does not encounter too much current draw at once
}

// Initialize all the servos for the wrist, setting initial positions accordingly
void initWrist()
{
  wristUD.attach(wristUDPin);
  wristLR.attach(wristLRPin);
  wristUD.write(60);
  wristLR.write(90);
  delay(100); // Small delay to ensure the power supply does not encounter too much current draw at once
}

// Initialize all the led pins to output
void initRGB()
{
  pinMode(redPin, OUTPUT);
  pinMode(greenPin, OUTPUT);
  pinMode(bluePin, OUTPUT);
}

// Initialize all the pressure sensor pins to input
void initSensor()
{
  pinMode(fsrPin, INPUT);
}

// Initialize elbow servo pin, setting initial value to being perpendicular to the wood plank
void initElbow()
{
  elbow.attach(elbowPin);
  elbow.write(15);
}

// Function to control the color of the LED as either red, green, or blue (RGB)
void RGB(uint8_t redValue, uint8_t greenValue, uint8_t blueValue)
{
```

```
  analogWrite(redPin, redValue);
  analogWrite(greenPin, greenValue);
  analogWrite(bluePin, blueValue);
}

// Function to move the fingers into the palm (grip)
void grip()
{
  pPos = pointer.read();
  mPos = ringmiddle.read();
  pinkyPos = pinky.read();
  Serial.println(pPos);
  if (pPos > 0)
  {
    pPos -= 1;
  }

  if (mPos < 180)
  {
    mPos += 1;
  }

  pinky.write(pPos);
  ringmiddle.write(mPos);
  pointer.write(pPos);
  delay(20);
}

// Function to move the fingers out the palm (extension of fingers)
void release()
{
  pPos = pointer.read();
  mPos = ringmiddle.read();
  pinkyPos = pinky.read();
  Serial.println(pPos);

  if (pPos < 180)
  {
    pPos += 1;
  }

  if (mPos > 0)
  {
    mPos -= 1;
  }
```

```
  pinky.write(pPos);
  ringmiddle.write(mPos);
  pointer.write(pPos);
  delay(20);
}

// Moves the thumb into the palm
void thumbAdjIn()
{
  tPos = thumb.read();

  if (tPos > 0)
  {
    tPos -= 1;
  }
  thumb.write(tPos);
  delay(20);
}

// Moves the thumb out of the palm
void thumbAdjOut()
{
  tPos = thumb.read();
  if (tPos < 180)
  {
    tPos += 1;
  }
  thumb.write(tPos);
  delay(20);
}

// Moves the hand up (palm facing the ground)
void wristUP()
{
  uint8_t wristUDpos = wristUD.read();
  if (wristUDpos < 170)
  {
    wristUDpos += 1;
  }
  wristUD.write(wristUDpos);
  delay(20);
}

// Moves the hand down (palm facing the ground)
void wristDOWN()
{
```

```
  uint8_t wristUDpos = wristUD.read();
  if (wristUDpos > 15)
  {
   wristUDpos -= 1;
  }
  wristUD.write(wristUDpos);
  delay(20);
}

// Moves the hand counterclockwise (ccw) (palm facing the ground)
void wristLEFT()
{
  uint8_t wristLRpos = wristLR.read();
  if (wristLRpos < 115)
  {
   wristLRpos += 1;
  }
  wristLR.write(wristLRpos);
  delay(20);
}

// Moves the hand clockwise (cw) (palm facing the ground)
void wristRIGHT()
{
  uint8_t wristLRpos = wristLR.read();
  if (wristLRpos > 0)
  {
   wristLRpos -= 1;
  }
  wristLR.write(wristLRpos);
  delay(20);
}

// Moves the arm down (parallel to the mount / table)
void elbowDOWN()
{
  uint8_t epos1 = elbow.read();
  if (epos1 < 80)
  {
   epos1 += 1;
  }
  elbow.write(epos1);
  delay(20);
}

// Moves the arm up (perpendicular to the mount / table)
```

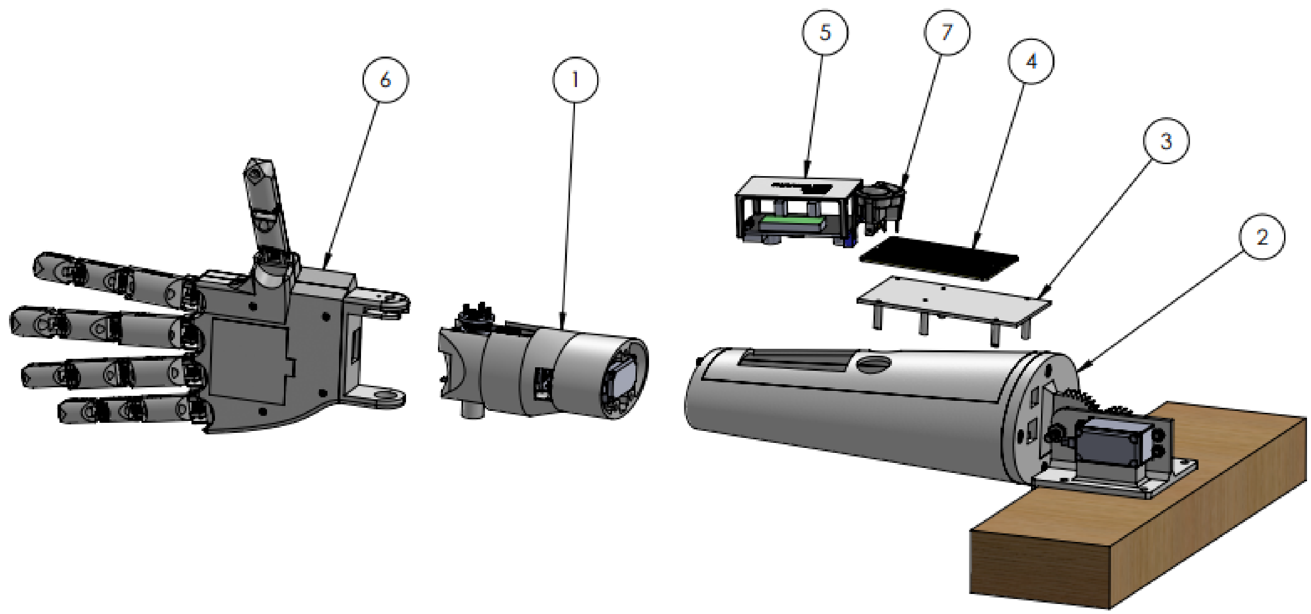
```
void elbowUP()
{

  uint8_t epos1 = elbow.read();
  if (epos1 > 0)
  {
    epos1 -= 1;
  }
  elbow.write(epos1);
  delay(20);
}

// grip egg
void gripEgg()
{
  uint16_t fsrVal = analogRead(fsrPin);
  pPos = pointer.read();

  // stops pnly when either the tolerance on the fsr is met or the servo can not grip any further
  while (fsrVal <= 300)
  {
    pPos = pointer.read();
    while (thumb.read() > 0)
    {
      thumbAdjIn();
    }
    grip();
    if (pPos == 1)
    {
      break;
    }
  }
  //Serial.println("done");
}

// grip Cue ball
void gripCueBall()
{
  uint16_t fsrVal = analogRead(fsrPin);
  pPos = pointer.read();

  // stops when either the tolerance on the fsr is met or the servo can not grip any further
  while (fsrVal <= 650 || pPos > 5)
  {
    pPos = pointer.read();
    while (thumb.read() > 0)
```

```
    {
      thumbAdjIn();
    }
    grip();
    if (pPos == 1)
    {
      break;
    }
  }
}

// initial start up code to test that hand servos are connected correctly
void rigorMortis()
{
  if (GamePad.isUpPressed())
  {
    pinky.write(0);
  }
  if (GamePad.isDownPressed())
  {
    pinky.write(180);
  }
  if (GamePad.isLeftPressed())
  {
    ringmiddle.write(0);
  }
  if (GamePad.isRightPressed())
  {
    ringmiddle.write(180);
  }
  if (GamePad.isTrianglePressed())
  {
    pointer.write(0);
  }
  if (GamePad.isSquarePressed())
  {
    pointer.write(180);
  }
}

// Function to check buttons for moving wrist and elbow
void adjustWristElbow()
{
  Dabble.processInput(); // Process button clicks from Dabble App

  // Moves the arm up when square (□) is pressed
```

```
  if (GamePad.isSquarePressed())
  {
    elbowUP();
  }

  // Moves the arm down when circle (o) is pressed
  if (GamePad.isCirclePressed())
  {
    elbowDOWN();
  }

  // Moves the hand up when up (^) is pressed (palm facing down)
  if (GamePad.isUpPressed())
  {
    wristUP();
  }

  // Moves the hand down when down (v) is pressed (palm facing down)
  if (GamePad.isDownPressed())
  {
    wristDOWN();
  }

  // Moves the hand ccw when left (<) is pressed (palm facing down)
  if (GamePad.isLeftPressed())
  {
    wristLEFT();
  }

  // Moves the hand cw when right (>) is pressed (palm facing down)
  if (GamePad.isRightPressed())
  {
    wristRIGHT();
  }
}

// Function to check Dabble buttons for moving fingers and thumb
void adjustHand()
{
  Dabble.processInput(); // Process button clicks from Dabble App

  // Closes hand when triangle (v) is pressed
  if (GamePad.isDownPressed()) // && !triangleButState)
  {
    grip();
  }
```

```
  // Opens hand when cross (^) is pressed
  if (GamePad.isUpPressed())
  {
   release();
  }

  // Moves thumb away from palm when right (>) is pressed
  if (GamePad.isRightPressed() && !startButState)
  {
   thumbAdjOut();
  }

  // Moves thumb into the palm when left (<) is pressed
  if (GamePad.isLeftPressed())
  {
   thumbAdjIn();
  }

  // Grips egg when the triangle (Δ) button is pressed
  if (GamePad.isTrianglePressed())
  {
   gripEgg();
  }

  // Grips cueball when the square (□) button is pressed
  if (GamePad.isSquarePressed())
  {
   gripCueBall();
  }
}
```

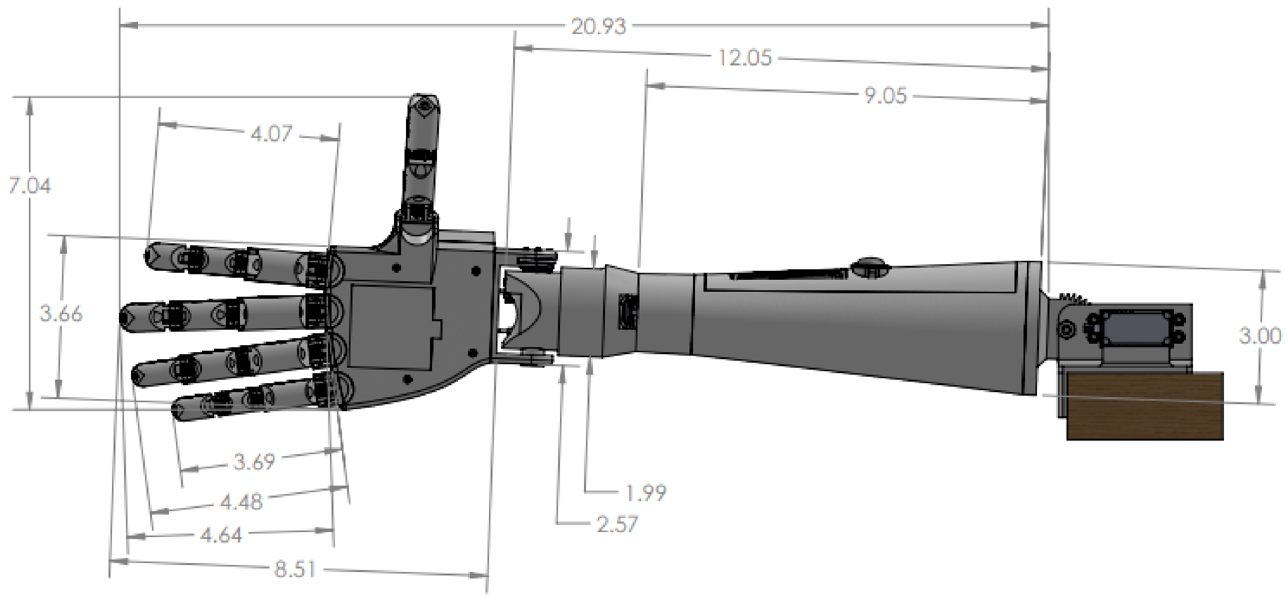
Appendix F - Drawings



ITEM NO.	FILE NAME	QTY.
1	Wrist Assembly Final	1
2	Elbow Assembly Final	1
3	ArduinoMega	1
4	Adafruit 1-Half Breadboard.step	1
5	DROK Buck Converter	1
6	Palm Final Sub Assembley	1
7	Rocker Switch With LED Indicator.stp	2

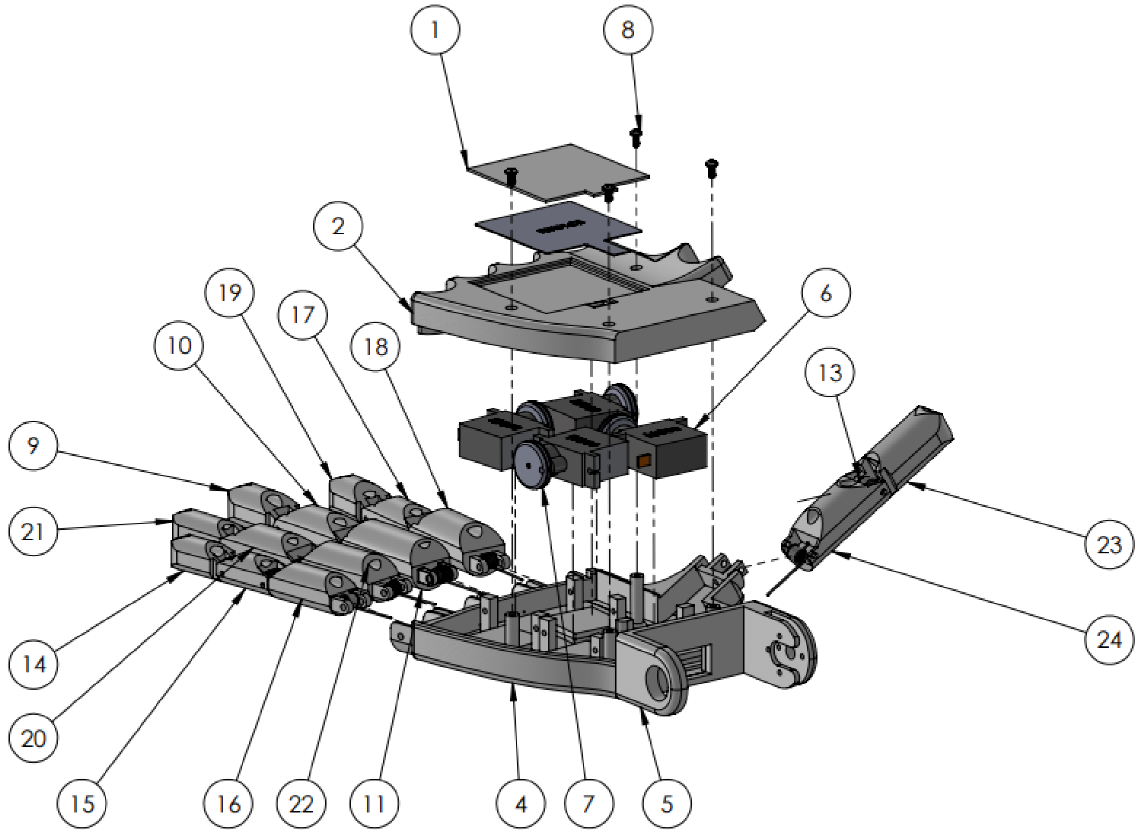
KSU 2 - 3D PRINTED PROSTHETIC ARM			
FILE NAME	FULL ASSEMBLY FINAL		
DESCRIPTION	EXPLODED VIEW & BOM OF FINAL ASSEM		
DRAWN BY	KSU 2	SCALE 1:8	SHEET 1 OF 2
TOLERANCES	.XX ± .01"	.XXX ± .005"	UNLESS OTHERWISE SPECIFIED

Figure F1. Full Arm Exploded View



KSU 2 - 3D PRINTED PROSTHETIC ARM			
FILE NAME	FULL ASSEMBLY		
DESCRIPTION	ROUGH OVERALL DIMENSIONS		
DRAWN BY	KSU 2	SCALE 1:8	SHEET 2 OF 2
TOLERANCES	.XX ± .01"	.XXX ± .005"	UNLESS OTHERWISE SPECIFIED

Figure F2. General Dimensions of the Prosthetic Arm



KSU 2 - 3D PRINTED PROSTHETIC ARM			
FILE NAME	PALM ASSEMBLY		
DESCRIPTION	EXPLODED VIEW OF PALM ASSEMBLY		
DRAWN BY	KSU 2	SCALE 1:8	SHEET 1 OF 2
TOLERANCES	.XX ± .01"	.XXX ± .005"	UNLESS OTHERWISE SPECIFIED

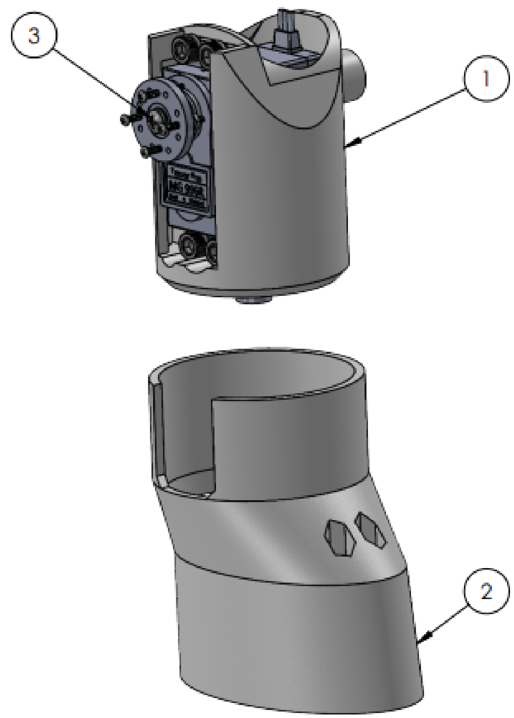
Figure F3. Exploded View of Palm Assembly

ITEM NO.	FILE NAME	DESCRIPTION	QTY.
1	fsr cover	Force sensor cover	1
2	Palm Lid Final	Bottom of palm	1
3	FSR	Force sensor	1
4	Palm Final	Top of palm	1
5	Wrist Connector Final	C-Shaped connector to wrist	1
6	SERVO_MG90	Servos used in palm	4
7	Spool Final	Spool used for finger movement	4
8	91249A046	2-56 McMaster Carr bolts	4
9	middle	Middle finger distal phalange	1
10	middle	Middle finger intermediate phalange	1
11	middle	Middle finger proximal phalange	1
12	9271K94	Torsion spring for joints inbetween phalanges	2
13	9271K94		12
14	pinky	Pinky finger distal phalange	1
15	pinky	Pinky finger intermediate phalange	1
16	pinky	Pinky finger proximal phalange	1
17	pointer	Pointer finger distal phalange	1
18	pointer	Pointer finger intermediate phalange	1
19	pointer	Pointer finger proximal phalange	1
20	Ring2.FinalConfig	Ring finger distal phalange	1
21	Ring1.FinalConfig	Ring finger intermediate phalange	1
22	Ring3.FinalConfig	Ring finger proximal phalange	1
23	thumb	Thumb finger distal phalange	1
24	thumb	Thumb finger proximal phalange	1

KSU 2 - 3D PRINTED PROSTHETIC ARM

FILE NAME	PALM ASSEMBLY		
DESCRIPTION	BILL OF MATERIALS FOR PALM		
DRAWN BY	KSU 2	SCALE 1:8	SHEET 2 OF 2
TOLERANCES	.XX ± .01"	.XXX ± .005"	UNLESS OTHERWISE SPECIFIED

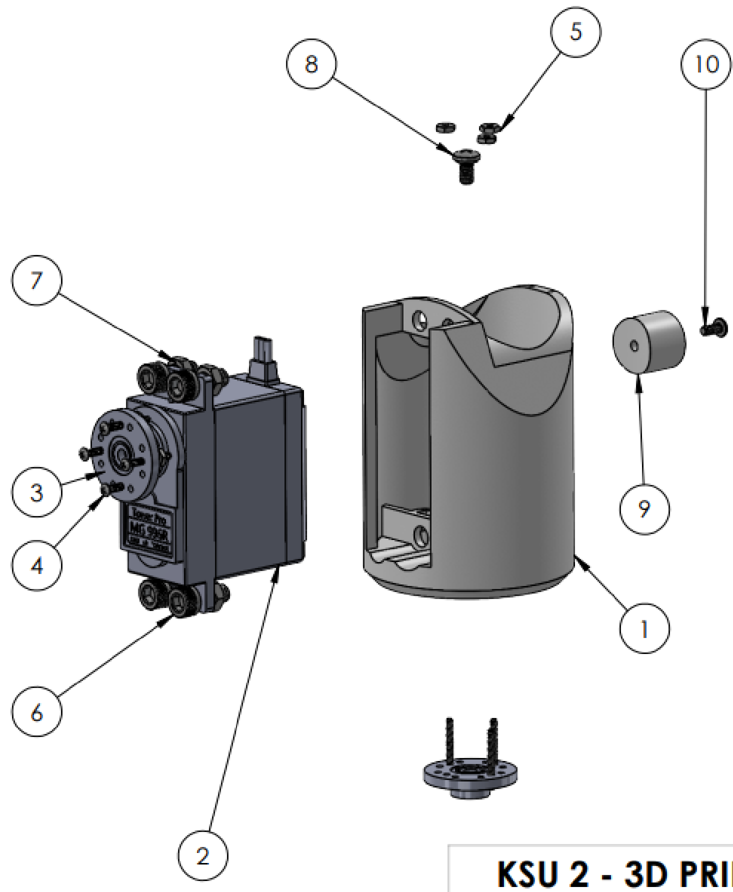
Figure F4. BOM For Palm Assembly



ITEM NO.	FILE NAME	DESCRIPTION	QTY.
1	Top Wrist SubAssembly	TOP WRIST	1
2	Bottom Wrist SubAssembly	BOTTOM WRIST	1
3	92000A114	Passivated 18-8 Stainless Steel Pan Head Phillips Screws	1

KSU 2 - 3D PRINTED PROSTHETIC ARM			
FILE NAME	WRIST ASSEMBLY FINAL		
DESCRIPTION	FULL WRIST EXPLODED VIEW & BOM		
DRAWN BY	KSU 2	SCALE 1:4	SHEET 1 OF 1
TOLERANCES	.XX ± .01"	.XXX ± .005"	UNLESS OTHERWISE SPECIFIED

Figure F5. Exploded View of the Wrist Assembly



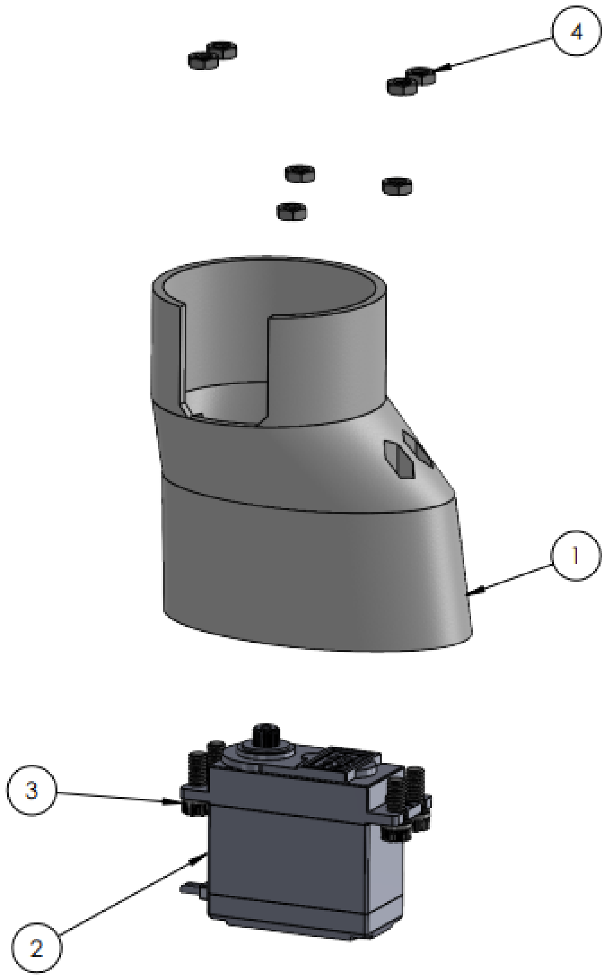
KSU 2 - 3D PRINTED PROSTHETIC ARM			
FILE NAME	TOP WRIST SUBASSEMBLY		
DESCRIPTION	EXPLODED VIEW OF TOP WRIST		
DRAWN BY	KSU 2	SCALE 1:2	SHEET 1 OF 2
TOLERANCES	.XX± .01"	.XXX ± .005"	UNLESS OTHERWISE SPECIFIED

Figure F6. Exploded View of Top Wrist Subassembly

ITEM NO.	FILE NAME	DESCRIPTION	QTY.
1	Wrist cylinder Final	Top wrist	1
2	Servo_Motor_MG996R	Servos for wrist	1
3	Servo Horn	Horns that come with Servos	2
4	91772A059	Passivated 18-8 Stainless Steel Pan Head Phillips Screw	7
5	96537A145	18-8 Stainless Steel Hex Nut	7
6	91251A192	Black-Oxide Alloy Steel Socket Head Screw	4
7	90760A009	Steel Narrow Hex Nuts	4
8	92000A114	Passivated 18-8 Stainless Steel Pan Head Phillips Screws	1
9	palm to wrist bearing Final	Bearing for palm	1
10	91249A046	Black-Oxide 18-8 Stainless Steel Pan Head Phillips Screws	1

KSU 2 - 3D PRINTED PROSTHETIC ARM			
FILE NAME	TOP WRIST SUBASSEMBLY		
DESCRIPTION	BILL OF MATERIALS FOR TOP WRIST		
DRAWN BY	KSU 2	SCALE 1:2	SHEET 2 OF 2
TOLERANCES	.XX ± .01"	.XXX ± .005"	UNLESS OTHERWISE SPECIFIED

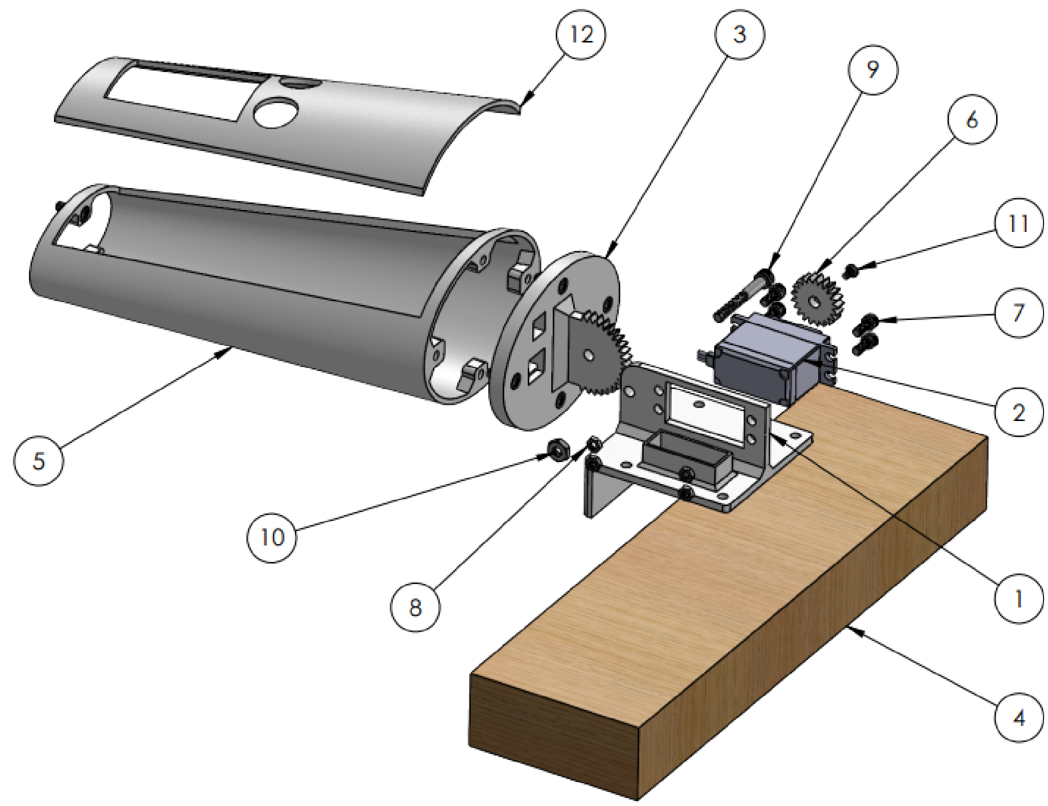
Figure F7. BOM for Top Wrist Subassembly



ITEM NO.	FILE NAME	DESCRIPTION	QTY.
1	Bottom wrist Final	Bottom Wrist Housing	1
2	Servo_Motor_MG996R	Wrist Servo	1
3	91251A192	Black-Oxide Alloy Steel Socket Head Screw	4
4	90760A009	Steel Narrow Hex Nuts	7

KSU 2 - 3D PRINTED PROSTHETIC ARM			
FILE NAME	BOTTOM WRIST SUBASSEMBLY		
DESCRIPTION	BOTTOM WRIST EXPLODED VIEW & BOM		
DRAWN BY	KSU 2	SCALE 1:4	SHEET 1 OF 1
TOLERANCES	.XX ± .01"	.XXX ± .005"	UNLESS OTHERWISE SPECIFIED

Figure F8. Exploded View and BOM for Bottom Wrist Subassembly



KSU 2 - 3D PRINTED PROSTHETIC ARM			
FILE NAME	ELBOW ASSEMBLY FINAL		
DESCRIPTION	EXPLODED VIEW OF ELBOW ASSEMBLY		
DRAWN BY	KSU 2	SCALE 1:8	SHEET 1 OF 2
TOLERANCES	.XX ± .01"	.XXX ± .005"	UNLESS OTHERWISE SPECIFIED

Figure F9. Exploded View of Elbow Assembly

ITEM NO.	FILE NAME	DESCRIPTION	QTY.
1	Elbow Mount Final	Mount for servo and 2x4	1
2	Servo_Motor_MG996R	Servo used for rotation of elbow	1
3	Elbow Connector Final	End cap for forearm	1
4	2x4 wood	Wood	1
5	Forearm Final	Main forearm piece	1
6	Elbow Servo Gear Final	Gear to mount onto servo	1
7	91251A192	Black-Oxide Alloy Steel Socket Head Screw	11
8	90760A009	Steel Narrow Hex Nuts	8
9	91251A251	Black-Oxide Alloy Steel Socket Head Screw	1
10	90480A011	Low-Strength Steel Hex Nut	1
11	92000A114	Passivated 18-8 Stainless Steel Pan Head Phillips Screws	1
12	Forearm Cover Final	Cover for the forearm electronics	1

KSU 2 - 3D PRINTED PROSTHETIC ARM			
FILE NAME	ELBOW ASSEMBLY FINAL		
DESCRIPTION	BILL OF MATERIALS FOR ELBOW		
DRAWN BY	KSU 2	SCALE 1:2	SHEET 2 OF 2
TOLERANCES	.XX ± .01"	.XXX ± .005"	UNLESS OTHERWISE SPECIFIED

Figure F10. BOM for Elbow Assembly

Appendix G - Bill of Materials (BOM)

Item No.	Sub-Assembly	File Name	Quantity	Description
1	Palm	fsr cover	1	Force sensor cover
2		Palm Lid Final	1	Bottom of palm
3		FSR	1	Force sensor
4		Palm Final	1	Top of palm
5		Wrist Connector Final	1	C-shaped connector to wrist
6		Servo MG90	4	Servos used in palm
7		Spool Final	4	Spool used for finger movement
8		(not modeled)	8	Mounting screws for servo (comes with each servo)
9		(not modeled)	4	Mounting screws for spool to servo
10		91249A046	4	McMaster Carr Black-Oxide 18-8 Stainless Steel Pan Head Phillips Screws
11		Middle1.FinalConfig	1	Middle finger distal phalange
12		Middle2.FinalConfig	1	Middle finger intermediate phalange
13		Middle3.FinalConfig	1	Middle finger proximal phalange
14		Point1.FinalConfig	1	Pointer finger distal phalange
15		Point2.FinalConfig	1	Pointer finger intermediate phalange
16		Pointer3.FinalConfig	1	Pointer finger proximal phalange
17		Ring1.FinalConfig	1	Ring finger distal phalange
18		Ring2.FinalConfig	1	Ring finger intermediate phalange
19		Ring3.FinalConfig	1	Ring finger proximal phalange
20		Pinky1.FinalConfig	1	Pinky finger distal phalange
21		Pinky2.FinalConfig	1	Pinky finger intermediate phalange
22		Pinky3.FinalConfig	1	Pinky finger proximal phalange
23		Thumb1.FinalConfig	1	Thumb finger distal phalange
24		Thumb2.FinalConfig	1	Thumb finger proximal phalange
25		Torsion Spring	14	Torsion spring for joints inbetween phalanges

26	Wrist	Wrist Cylinder Final	1	Top wrist cylinder to mount up and down servo
27		90760A009	11	8-32 McMaster Carr Steel Narrow Hex Nuts
28		91251A192	8	8-32 Black-Oxide Alloy Steel Socket Head Screw
29		Servo_Motor_MG996R	2	Servos used in wrist
30		Servo Horn	2	Servo horn that comes with servo
31		91772A059	7	0-80 Passivated 18-8 Stainless Steel Pan Head Philips Screw
32		96537A145	7	0-80 Stainless Steel Hex Nut
33		92000A114	2	M3 Passivated 18-8 Stainless Steel Pan Head Phillips Screws
		91249A046	1	2-56 Black-Oxide 18-8 Stainless Steel Pan Head Phillips Screws
34		Palm to Wrist Bearing Final	1	Bearing for side of top wrist
35		Bottom Wrist Final	1	Bottom housing of wrist
36	Elbow	Elbow Mount Final	1	Mount for servo and 2x4
37		Servo_Motor_MG996R	1	Servo used for rotation of elbow
38		Elbow Connector Final	1	End cap for forearm
39		2x4 Wood	1	Wood
40		Forearm Final	1	Main forearm piece
		Forearm Cover Final	1	Cover for the forearm electronics
41		Elbow Servo Gear Final	1	Gear to mount onto servo
42		90760A009	8	8-32 McMaster Carr Steel Narrow Hex Nuts
43		91251A192	11	8-32 Black-Oxide Alloy Steel Socket Head Screw
44		92000A114	1	M3 Passivated 18-8 Stainless Steel Pan Head Phillips Screws
45		91251A251	1	10-24 Black-Oxide Alloy Steel Socket Head Screw
46		90480A011	1	10-24 Low-Strength Steel Hex Nut

Appendix H - Gantt Chart