# Active Wrist Joint for Below-the-Elbow Prosthesis

ME450 Section 002 Team 21 - Fall 2020

University of Michigan

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# Executive Summary

For the MECHENG 450 course, our team has completed the tasks of researching and benchmarking current bionic prosthetic devices and technology, generating engineering specifications from our stakeholder requirements, and creating preliminary designs for our below-the-elbow bionic prosthesis with an active wrist joint. Bionic prostheses are devices that seek to replace limbs or body parts with an artificial limb or part that is electronically or mechanically powered. Our project is a student initiated project that seeks to develop an open-source, bionic prosthesis with an active wrist joint for below-the-elbow amputations. The goal of this project is to have our device emulate the movement and load capacity required by the human wrist to fulfill typical activities of daily living, or ADLs. This active wrist provides users with one active degree of freedom (DoF) that imitates the biological flexion/extension movement of the human wrist. The ADLs that we have selected to base the requirements of our device on are: eating, maintaining personal hygiene, getting dressed, and carrying groceries. Due to time constraints, this project did not investigate the prosthesis-user interface. Moreover, the device includes a hand subsystem that has basic finger actuation. Functionality for this subsystem is restricted to simply opening and closing the fingers as the hand is not a focus of this project.

The requirements for the active wrist joint have been set through researching the needs of amputees while performing typical ADLs, benchmarking current industry equivalents, and meeting with our stakeholder Dr. Elliott Rouse, who works extensively with bionic prostheses. The wrist has one active DoF, flexion/extension, and one passive DoF, pronation/supination. Although the active capabilities of the wrist are a project focus, passive pronation/supination is included so that the developed device is an improvement on industry benchmarks that include this passive motion.

The active functionality of the wrist and fingers of the prosthesis must be able to be controlled with the muscular signals from the user's body. This requirement was not completed during the semester due to time constraints. Additionally, the wrist joint must have a load carrying capacity that can sustain loads encountered during our selected ADLs. The bionic prosthesis must also be aesthetically appealing to users, a requirement that was highly emphasized by our stakeholder. Other requirements for the active wrist system include: lightweight, durable, scalable, open-source, as well as water, debris, and detergent resistant. These requirements were then translated into engineering specifications by referencing industry benchmarks, relevant literature regarding our ADLs, and testing data.

Using these requirements, our team generated several design concepts for the device using methods such as brainstorming, morphological analysis, and design heuristic cards. When generating ideas, they were divided up based on the three main systems of the prosthetic device. These systems include: the active flexion/extension drive system, the passive pronation/supination system, and the power source system. From these generated designs, our team selected the most promising and practical ideas for each of the systems to develop further. These selected designs were then evaluated against one another using Pugh charts to determine the best idea.

After selecting the best concept, we conducted engineering analyses to develop our final design solution. The engineering analyses that were performed helped to select the transmission ratio, components, and

electrical requirements of the final design solution based on the engineering specifications we selected. The components that were specifically investigated were the belt and gears that compose the transmission system as well as the motor actuator that drives active flexion/extension. These components were analyzed using equations such as the electromechanical equations from MECHENG 350 and 360 for our motor as well as the Lewis equation for our gear strength. Using the final generated design solution, a complete CAD model was created.

Prototyping and simulation software were employed to verify that our final generated design solution fulfilled our specified requirements. However, it is important to note that due to limitations on time and the difficulties incurred by COVID-19, the prototype did not include a fully realized hand subsystem. Through our testing and simulation, we verified that the current design did or had the ability to fulfill its engineering specifications, excluding load bearing capacity and integrated power source. Additionally, the idealized goal of having the arm weigh ≤1 kg for our lightweight engineering specification was not met. However, the prototype still met the lightweight engineering specification as it weighed less than that of an average, adult human forearm. Although not all of our specified requirements were met with our current design, further design iterations will allow us to develop a prototype that achieves all of these requirements.

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# Project Report

## 1. Problem Description

The loss of limbs can significantly impact people's way of life and ability to fulfill daily activities. When compared to able-bodied individuals, amputees experience a significant restriction in mobility and loss of competency performing activities of daily living, or ADLs [1][2]. ADLs encompass a wide range of tasks and skills required by an individual to independently care for themselves. Examples of typical ADLs are: feeding, dressing, and cleaning oneself [3]. Passive upper-limb prostheses like the one shown below in Figure 1 provide amputees with the appearance of a biological arm but do not return any form of mobility or functionality [4]. When possible, body-powered prostheses are the standard solution used to partially restore functionality to upper-limb amputees. Unfortunately, while prosthetic devices such as the one shown below in Figure 1 by Ottobock offer amputees some assistance in carrying out ADLs, they do not offer the same range of motion as their biological counterparts [5].

**Figure 1.** (Left) Passive upper-limb prosthesis by Ottobock that serves users solely for aesthetic reasons as it only represents a biological limb in appearance [4]. (Right) Body-powered upper-limb prosthesis that provides users with utility in the form of a grasping mechanism but has a restricted range of motion [5].

While the body-driven prosthetic hand mechanism of Ottobock's body-powered upper-limb prostheses offers gripping capabilities to amputees, they do not restore a natural range of motion and performance. However, bionic prostheses offer a way to bridge this mobility and functionality gap between prostheses and their biological counterparts. The field of bionic prosthetics is a new, emerging field that offers to provide users with almost natural utility and mobility [6]. However, many of the below-the-elbow bionic prosthetics on the market are very expensive and require manual mechanical input from the user to move/rotate their wrist joints [7][8]. Thus, this project seeks to develop an open-source, bionic prosthesis with an active wrist joint for below-the-elbow amputations. The hand-wrist system emulates the movement and load capacity required by the human wrist to fulfill typical ADLs. The ADLs of interest for this project are: feeding, dressing, and cleaning oneself. Due to weight, time, and spatial constraints, the developed bionic prosthetic device provides users with only one degree of freedom (DoF) that imitates the biological movement of the human wrist. Based on the chosen ADLs, the motion of wrist flexion and extension was determined to be the most critical DoF [3][9]. Although the developed prosthesis includes a hand subsystem, it is not a focus of this project and its functionality is restricted to simply opening and closing. The hand subsystem is included in this project to better showcase the range of motion of the active wrist and act as a placeholder for future development of the prosthesis's capabilities. Additionally, this project did not investigate the prosthesis-user interface due to time constraints.

# 2. Background

*2.1 Anatomy and Motion*

The overall scope of this project is focused on designing an active flexion and extension system for the wrist joint. Flexion and extension are defined as the up/down pivot of the hand relative to the arm. This motion is shown in Figure 2 below.

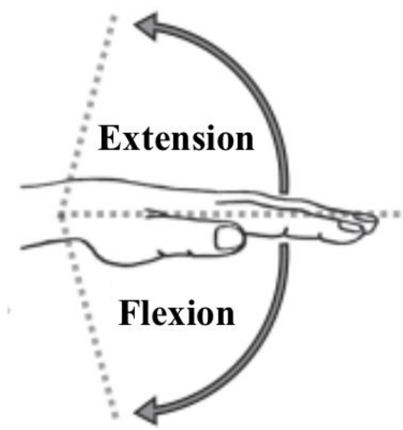



**Figure 2.** Flexion and extension of the wrist illustrated. Extension is an upwards movement relative to the forearm, while flexion is downwards. [6]

In addition to the flexion and extension motion, the device's design also integrates passive pronation and supination as this is a motion that is integrated into the designs of current industry benchmarks. Pronation and supination refer to the rotation of the hand about the lengthwise axis of the arm. This motion is shown below in Figure 3.

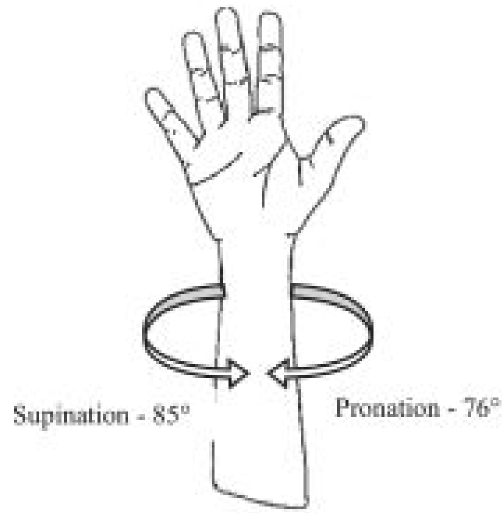



**Figure 3.** Pronation and supination of the wrist illustrated. Pronation is the clockwise motion about the axis of the arm, and supination is the counterclockwise motion. [6]

The pronation/supination motion of the prosthetic arm is passive, similar to the prosthetics that were benchmarked. This means that the motion is powered entirely by the user, and has no mechanical or electrical actuation system. In contrast, the flexion extension motion is active, meaning that it is powered and controlled by an electric or mechanical actuator. Thus, this project's wrist design improves upon current industry benchmarks by adding active flexion/extension in addition to the already included passive pronation/supination. These industry benchmarks are covered further in Section 2.2 below.

In addition, distal and proximal are two terms that are used in this report. Distal refers to further from the body, while proximal refers to closer to the body. Figure 4 below demonstrates this terminology.

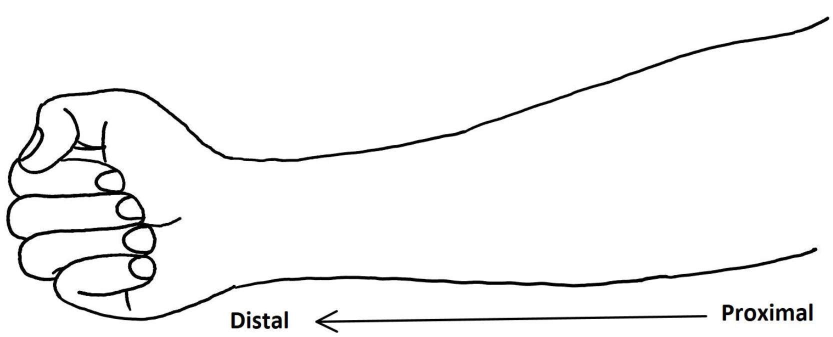



**Figure 4.** Visual representation of proximal and distal.

As shown in the figure above, the distal end of the arm is towards the fingers, whereas the proximal end is towards the shoulder. Note that distal and proximal can be generalised to refer to further and closer, respectively.

*2.2 Benchmarking*

The initial background research that was performed was a benchmark of current advanced bionic prostheses for below-the-elbow amputees. The first prosthesis benchmarked was the Hero Arm by Open Bionics, and the second was the Michelangelo by Ottobock, both shown below in Figure 5 [7][8].

**Figure 5a.** Hero Arm by Open Bionics provides users with flexion/extension functionality of fingers and significant finger articulation. However, the prosthesis lacks an active wrist joint. [7]

**Figure 5b.** Michelangelo prosthetic device by Ottobock provides users with flexion/extension and abduction/adduction functionality of fingers. The prosthesis also offers significant finger articulation. However, the prosthesis lacks an active wrist joint. [8]

The Hero Arm is unique in that it is the first bionic prosthetic that is primarily 3D-printed. This allows Open Bionics to sell the device for significantly less than its competitors, at approximately $3,000 as of 2019 [10]. In contrast, the Michelangelo prosthetic hand, by Ottobock, costs users $60,000 for approximately the same degree of functionality [8]. The Michelangelo prosthetic hand is considered one of the best on the market in terms of functionality and useability, as of 2015 [11]. The functionality provided by both arms includes control of flexion and extension of all fingers. The Michelangelo also has functionality for abduction and adduction of both the index and ring fingers [8]. However, both prostheses are lacking in powered-wrist control. Both Hero Arm and Michelangelo require direct mechanical user input to reorient the wrist relative to the arm. Figure 6 below shows how a user changes the wrist orientation of the Hero Arm manually.

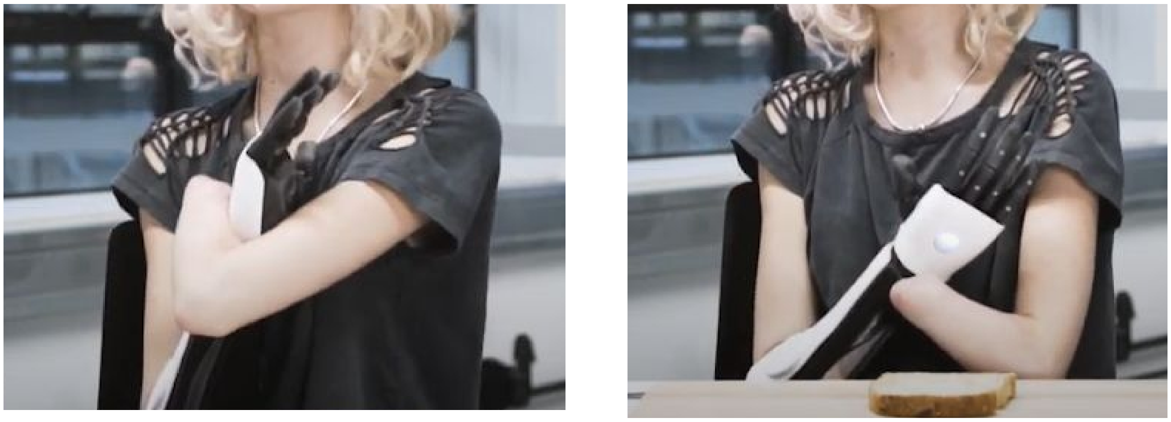


**Figure 6.** Left to right shows the change in orientation of the Hero Arm Prosthetic. This operation is manual and requires direct user input. [12]

As shown in the figure above, the user is required to perform mechanical work in order to reorient the hand. Once reoriented both prosthetic systems have mechanisms to lock the hand-wrist system in the desired position or orientation. Both prostheses utilize specific wrist positions that the prosthetic arm locks into based on user input. Hero Arm has 6 such orientations, while Michelangelo has 7 orientations [7][8]. However, as mentioned, neither prosthetic arm has a motor assisting in the reorientation of the wrist to these positions. In both cases, the user must manually shift the hand to the desired wrist position.

At any wrist position, the Hero Arm is capable of lifting 8 kg of mass [7]. The Michelangelo system did not have any available data reflecting the load bearing capacity of the system. In addition, the Hero Arm has a total mass of 1 kg [7]. The Michelangelo hand system has a weight 0.51 kg [8]. However, there was no data available on the mass of the lower arm portion of the prosthetic system. The number of wrist positions, load bearing capacity, and mass of each system is tabulated in Table 1 below.

**Table 1.** Table containing the number of wrist orientations, the load bearing capacity, and the Mass of each Prosthetic system benchmarked. [7][8]

| Prosthesis | Wrist Orientations | Load Bearing Capacity (kg) | Mass of Arm (kg) |
|---|---|---|---|
| Hero Arm | 6 | 8 | 1.00 |
| Michelangelo | 7 | Not Available | 0.51 |

As shown in the table above, the prosthetic arm with the most available data is the Hero Arm. Thus, when engineering specifications were compiled based on user requirements, the Hero Arm was used primarily as the baseline.

# 3. Requirements

This section details the prioritized list of stakeholder requirements for this project that were then translated into engineering specifications. Justifications for the quantities of the engineering specifications are provided. The specifications that were drawn up were informed by the ADLs that the prosthetic system is designed to perform. These ADLs are eating, maintaining personal hygiene[1], getting dressed, and carrying groceries [6]. Maintaining hygiene includes washing hands, brushing teeth, combing hair, applying lotion, and applying deodorant. It does not include bathing or showering [6].

**Table 2.** Stakeholder requirements and the engineering specification derived from them. The justifications for the quantities within the specifications are also provided.

| Tier | Requirement | Specification | Justification |
|---|---|---|---|
| **Primary** | Mimics Human Wrist Motion | Flexion/Extension Motion:<br>70 degrees flexion<br>40 degrees extension<br>Wrist angular velocity of 2-3 rad/s<br>Passive Pronation/Supination | Wrist range of motion during ADLs [6]<br>Experimental testing of ADLs, see appendix A [19]<br>Device functionality should be comparable with industry benchmarks |
| | Load Bearing Capacity | Wrist load capacity ≥ 8 kg | Industry standard [7], prosthetics cannot lift as much as a human arm due to push/pull limitations. [13]<br>Weight of grocery bags [20] |
| | Lightweight | Full prosthetic mass ≤ 2.26 kg [21]<br>Ideally ≤ 1 kg so that it is comparable to industry benchmarks [7] | Increased mass can have negative effects on body/gait symmetry [14]<br>Increased mass correlates to increased exertion (20-25%) [15] |
| | Integrated Power Source | ≥ 12 hours of battery life untethered to computer | Prosthesis should function throughout the day [7][8] |

[1] It is important to note that the ADL of personal hygiene includes user activities such as: brushing teeth, combing hair, and washing hands but does not include: bathing or showering with the prosthetic device.

| Tier | Requirement | Specification | Justification |
|---|---|---|---|
| Secondary | Scalable | Scales to 3 different sizes | Industry standard size offerings [7][8] |
| | Water, Debris, and Detergent Resistant | Fully functional when submerged in water up to the wrist and when exposed to debris and detergent | Industry standard [8], water, debris, and detergent important part of ADLs |
| | Easy to Clean | Cleaning time ≤ 10 mins<br>Requires no special solutions | Industry standard ease of cleaning [7] |
| | Open-Source / Most Simple Design | All design decisions and rationale documented<br>Parts commercially available (≤ 5 suppliers)<br>Total cost ≤ $1000 | Design must be easy to follow and replicate to be open-source [16] |
| | Hand Functionality | Hand/finger placeholders that open and close | Need basic actuation to ensure room for future system |
| Future | Aesthetic | Score ≥7 on 10-point Likert scale<br>Operates ≤ 25 decibels | Important to amputees<br>Below the sound of a whisper (30 dB) [17] |
| | Controlled with Human Nervous System | Full functionality of wrist and fingers with signals from peripheral nerves in arms | Bionic limbs provide functionality and improve the quality of life of patients [15] |
| | Durable | Lifetime ≥ 2 million cycles | ISO 10328:2006 lower limb prosthesis standard, none found for upper limb [18] |

*3.1 Primary Requirements*

The stakeholder requirements of "Mimics Human Wrist Motion", "Load Bearing Capacity", "Lightweight", and "Integrated Power Control" were given the highest priority because they focus on the functionality of the wrist system. The wrist must emulate the motion of its biological inspiration, however time constraints of the project only allow the development of a device with one actuated degree of freedom (DoF). The device is capable of motion in the flexion/extension DoF, achieving a range of 70° of flexion and 40° of extension, the range of motion typically required for the selected activities of daily living: eating, maintaining personal hygiene, getting dressed, and carrying groceries [3][6][9]. Flexion /extension is the up down motion across the wrist as described in Figure 2 in Section 2.

The flexion/extension motion is actuated at a rate between 2 and 3 radians per second or about 115 to 172 degrees per second. This data was taken from a test performed by the team using the methodology specified by David Jessop and Mathew Pain [19]. Additionally, the angles of motion for the selected ADLs were measured along with the time to complete the motion and used to calculate this motion. This data can be found in appendix A. Additionally, the device also performs pronation/supination movements, as described in Figure 3 in Section 2, but this movement is not actuated. Pronation/supination refers to the rotation of the wrist to turn the palm downwards or upwards.

The device performs this motion as other industry benchmarks allow for passive pronation/supination movement, and the device seeks to be comparable in functionality.

Furthermore, the device must bear a load of up to 8 kg before failure, as is consistent with the Hero Arm industry benchmark [7]. The point of failure for the benchmarked protheses is believed to be the connection between the user and the prosthetic device; therefore, 8 kg was selected as the maximum load capacity for the device. The team searched for sources supporting or refuting this assertion but were unable to find anything due to the limited availability of technical data on the benchmarked prosthetics. Based on the knowledge of the team, and in the absence of a source, the team is proceeding under the assumption that the failure occurs at the connection between the user and the device, not as a result of a material failure in the device. Therefore, in order to ensure that the designed wrist system is compatible with other modern prosthetic devices, the specification was assigned based on the function of the benchmarks. Additionally, the selected value of 8 kg is larger than the expected loading for the ADLs. The activity of carrying groceries creates the largest loads of the ADLs, and the maximum expected load for this would be 17 lbs or 7.7 kg [20].

The device must also be lightweight, so as to not cause an undue metabolic burden on the user or affect their gait [14][15]. While information on the mass of industry benchmarks is sparse, the Hero Arm by Open Bionics has a mass of 1 kg, which this project has chosen to set as the maximum acceptable mass [7]. Additionally, a bionic wrist, by definition, requires a power source to function. To allow users to travel without an external power source, the device must have an internal power source that lasts throughout the day. The duration of a day, as considered by other commercial bionic devices, is 12 hours [7][8].

### *3.2 Secondary Requirements*

The stakeholder requirements of "Scalable", "Water, Debris, and Detergent Resistant", "Easy to Clean", "Open-Source/Most Simple Design", and "Hand Functionality" were given secondary priority due to their smaller significance in the basic functionality of the device. Rather than being critical for the device to function, these requirements address the needs of daily users and the inclusivity of the design to a wide patient population. Amputees come in all shapes and sizes, and to serve their needs, the device must fit the patient. To allow for a more commercializable design, rather than a custom fit, that still caters to size differences, the device must be scalable to three sizes, as is customary with industry benchmarks [7][8]. Additionally, the device must also be able to withstand exposure to water up to the wrist as well as debris and detergents that accompany ADLs such as personal hygiene [3][8][9]. The device must be easily cleaned so that the user can maintain their hygiene without extensive effort. Industry benchmarks specify a cleaning time of less than ten minutes and a process that requires no special cleaning solutions [7]. To ensure the device can be easily replicated by others, as is the purpose of open-sourcing, all design decisions and rationale have been documented [16]. Additionally, the non-3D-printed parts requiring purchase must be commercially available, and come from a small number of manufactures, which this project has limited to three. Furthermore, the total cost cannot exceed $400. Finally, while hand functionality is not in the scope of the project, place-holder digits of some kind with basic open/close actuation must be present to ensure room is available for future development of a more sophisticated hand system.

### *3.3 Future Requirements*

Due to the timeframe of the project, there are several stakeholder requirements that, while important to the end product, have not been addressed in the scope of this semester's project. These requirements are "Aesthetic", "Controlled with Human Nervous System", and "Durable." Aesthetics is considered the highest priority by Dr. Rouse, as it is, in his experience, the primary aspect of an amputee's satisfaction. The aesthetics of the device will be judged on a 10-point Likert scale, with the goal of achieving a score of 7 or higher. Additionally, the noise generated by the device must be 25 dB below ambient room sound. A normal human whisper is approximately 30 dB, which the device should be quieter than [17].

While not in the scope of this project, the wrist should eventually interface with the human nervous system to allow user control that mimics control of a biological wrist. Future development of the project should enable the device to function entirely with signals from muscles proximal to the amputation. Such bionic control has been shown to improve the patients' quality of life relative to a traditional prosthetic [15]. Additionally, this functionality must last throughout repeated use of the device. The ISO has not published lifecycle standards for upper-limb bionics, so this project has chosen to adhere to the ISO lower-limb durability specification of greater than two million cycles [18]. Though durability will be considered the design process, validation of the device's lifetime will not be possible given the time constraints of the project.

# 4. Concept Generation

This section details the concept generation process implemented for this project. Several forms of idea generation were implemented including: SCAMPER, morphological analysis, and design heuristics.

### *4.1 Idea Generation*

Each member of the team worked individually to generate at least ten ideas. These ideas could have been subsystem level, meaning it was a specific idea for one of our subsystem categories, or it could have been system level, which incorporated multiple or all subsystem categories. The three subsystem categories included: active flexion/extension drive systems, passive pronation/supination systems, and power source systems. After everyone had created their own ideas, the team came together and compiled them into their component categories. During this process the team was determined to keep an open mind and accept any and all ideas created by others in the group. Table 3 below shows a variety of the generated ideas divided into subsystems. Once compiled, SCAMPER and design heuristics were used to generate additional ideas from these ideas.

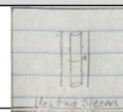
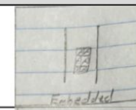
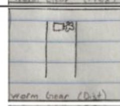
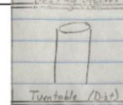
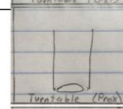
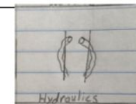
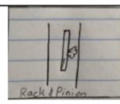
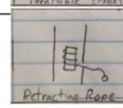
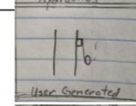
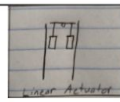
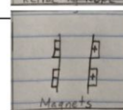
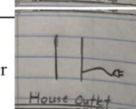
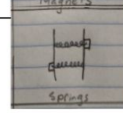
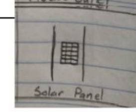
**Table 3.** Ideas generated in individual brainstorming and compiled together into subsystem categories.

| Active Flexion/ Extension Drive Systems | Passive Pronation/Supination Systems | Power Source Systems |
|---|---|---|
| 1. Worm Gear w/ Motor at Proximal End<br>2. Worm Gear w/ Motor at Distal End<br>3. Belt<br>4. Magic Motor<br>5. Rack and Pinion<br>6. Seesaw<br>7. Linear Actuator<br>8. Tension Wire<br>9. Magnets<br>10. Threaded Grooves<br>11. Rotini Pasta Worm Gears<br>12. Mirrored Motion | 1. Nesting Sleeves<br>2. Proximal Turntable<br>3. Distal Turntable<br>4. Mage Hand Spell<br>5. Magnetic Flux Pinning<br>6. Spring System<br>7. Telekinesis<br>8. Retractable Rope<br>9. Body Powered<br>10. Earth/Metalbending<br>11. Ask it Nicely<br>12. Manipulated by Puppeteer | 1. Embedded Battery<br>2. Wearable Battery<br>3. Hamsters Running on a Wheel<br>4. Hydraulics<br>5. User generated<br>6. Nuclear Power<br>7. Household Outlet<br>8. Solar Power<br>9. Flywheel<br>10. Bike Powered<br>11. Carbohydrate Powered<br>12. Diesel Engine |

### *4.2 Morphological Matrix*

Next, the ideas were pared down based on how practical they were. These practical ideas were taken and placed into a morphological matrix along with crude sketches to help visualize the ideas. It was determined that using morphological analysis would generate the most diverse combinations and would prevent tunnel vision or repeated choice of a favorite idea. Our morphological matrix can be seen below in Table 4.

**Table 4.** Morphological Matrix created from ideas generated in section 4.1

| | Active Flexion and Extension Drive | | Passive Pronation and Supination | | Power Source | |
|---|---|---|---|---|---|---|
| **1** | Worm gear w/ motor at proximal end |  | Nesting Sleeve |  | Embedded Battery |  |
| **2** | Worm gear w/ motor at distal end |  | Turntable @ distal end |  | Wearable Battery |  |
| **3** | Belt |  | Turntable @ proximal end |  | Hydraulics |  |
| **4** | Rack & Pinion |  | Retracting Rope System |  | User Generated Power |  |
| **5** | Linear Actuators |  | Attractant/ Repellent Magnets |  | Household Outlet Power |  |
| **6** | Tension Wires |  | Spring System |  | Solar Power Panels |  |

### *4.3 Design Combination Formation*

At this stage in the process, random combinations were determined by rolling a six-sided die three times. The first roll determined what the active flexion/extension drive system would be. The second roll determined what the passive pronation/supination system would be, and the third roll determined what the power source system would be.

Example combinations are:

| | |
|---|---|
| 1 + 2 + 6 | Worm gear driven flexion/extension with a turntable at the distal end for pronation /supination and solar power as a power source |
| 4 + 5 + 4 | Rack & Pinion drive system with attractant/repellent magnets and user generated power |

# 5. Concept Development

This section details development of the design concepts generated in Section 4. From the list of generated active flexion/extension drive systems ideas, six were considered practical and promising, and therefore they were selected to be further developed. Thus, drawings detailing the implementation of these ideas are shown below. Two of the three practical and promising passive pronation/supination system ideas from Section 4 are highlighted within these drawings. The hand subsystem for this project was not a priority for this project. Therefore, a well accepted system for basic finger actuation in bionics was selected. This method utilizes tensioning wires and motor actuators as shown in the drawings below. The developed designs also integrate a solution to one the secondary stakeholder requirements, which was to have the prosthetic device be water, debris, and detergent resistant. To achieve this, a wrist cover is used. The material, shape, and implementation of this secondary requirement solution will be further investigated as the team moves into the solution development stage of the project.

Additionally, this section showcases two of the three practical and promising power source systems from Section 4.

### *5.1 Design 1: Motor Actuator and Worm Gear with a Belt Transmission System*

A labeled drawing showcasing the first of these ideas is shown below in Figure 7. This design highlights the active flexion/extension drive system that is actuated by a motor and uses a belt coupled with a worm gear that the hand is rigidly attached to as a transmission system. The use of the worm gear prevents backdrive on the wrist. Therefore, the wrist does not need to be constantly driven by the drive system to retain its flexion/extension position. Meanwhile, the use of the belt allows a majority of the device's weight to be kept proximal to the user, thereby reducing the amount of strain on their arm. This design also highlights the passive pronation/supination system that uses a nested sleeve mechanism. This nested sleeve mechanism consists of an inner casing that houses the mechanisms of the prosthesis and rotates within an outer forearm cover. Mechanical user input is required to use this passive pronation/supination motion. Additionally, this specific design of the nested sleeve mechanism uses a ratchet mechanism at the wrist that allows the user to rotate the wrist to the desired pronation/supination position and have it stay. The wrist cover for water, debris, and detergent resistance as well as the simple finger actuation system are included in this drawing as well.

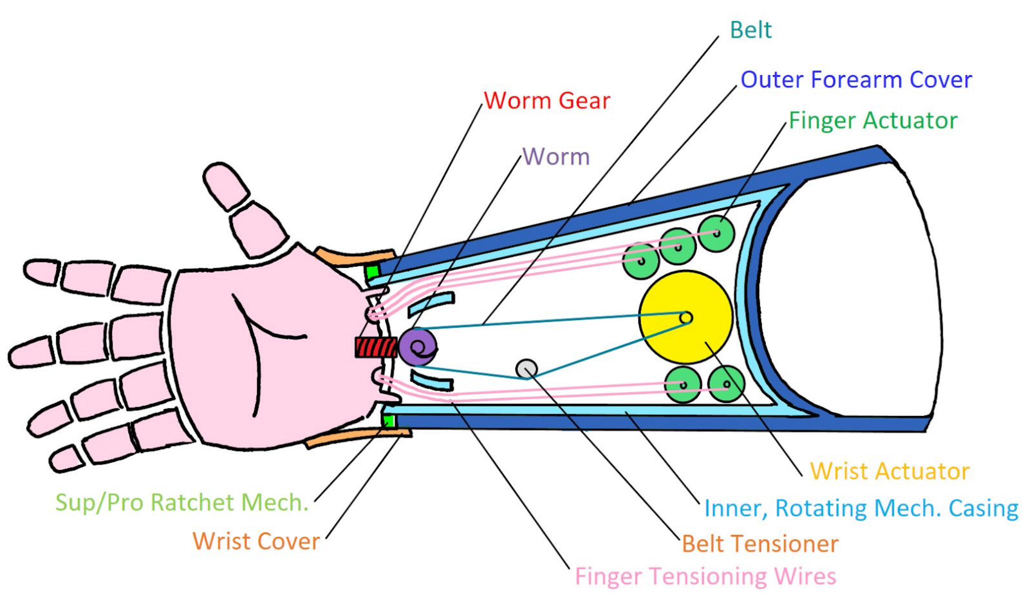



**Figure 7.** Labeled drawing showcasing the motor actuator with a belt coupled to a worm gear for the active flexion/extension drive system. Drawing showcases the nested sleeve mechanism for passive pronation/supination, too.

*5.2 Design 2: Motor Actuator and Worm Gear Transmission System*

A labeled drawing showcasing the second of these ideas is shown below in Figure 8. This design highlights the active flexion/extension drive system that is actuated by a motor and uses a worm gear at the distal end that the hand is rigidly attached to as a transmission system. The use of the worm gear prevents backdrive on the wrist. Therefore, the wrist does not need to be constantly driven by the drive system to retain its flexion/extension position. This design also highlights the passive pronation/supination system that uses a turntable mechanism. This turntable mechanism consists of an inner compartment that houses the mechanisms of the prosthesis and rotates on a turntable that is secured to an outer forearm cover. Mechanical user input is required to use this passive pronation/supination motion. Additionally, this specific design of the turntable mechanism uses a locking mechanism that allows the user to rotate the wrist to the desired pronation/supination position and lock its position. The wrist cover for water, debris, and detergent resistance as well as the simple finger actuation system are included in this drawing as well.

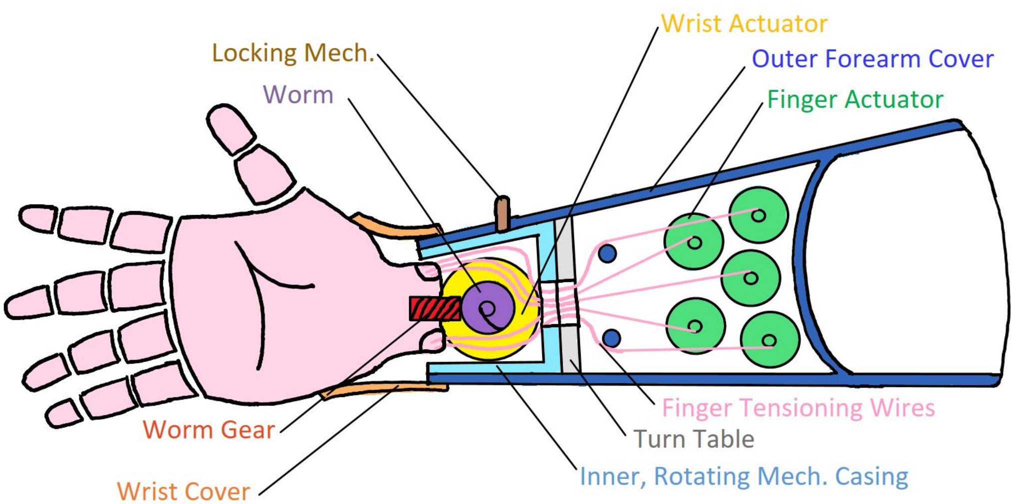



**Figure 8.** Labeled drawing showcasing the motor actuator with a worm gear for the active flexion/extension drive system. Drawing showcases the turntable mechanism for passive pronation/supination, too.

*5.3 Design 3: Motor Actuator and Belt Transmission System*

A labeled drawing showcasing the third of these ideas is shown below in Figure 9. This design highlights the active flexion/extension drive system that is actuated by a motor and uses a belt as a transmission system. The use of the belt allows a majority of the device's weight to be kept proximal to the user, thereby reducing the amount of strain on their arm. This active flexion/extension drive system also consists of a ratchet mechanism at the wrist. The use of the ratchet mechanism prevents backdrive on the wrist. Therefore, the wrist does not need to be constantly driven by the drive system to retain its flexion/extension position. This design also highlights the passive pronation/supination system that uses a nested sleeve mechanism. This nested sleeve mechanism consists of an inner casing that houses the mechanisms of the prosthesis and rotates within an outer forearm cover. Mechanical user input is required to use this passive pronation/supination motion. Additionally, this specific design of the nested sleeve mechanism uses a ratchet mechanism at the wrist that allows the user to rotate the wrist to the desired pronation/supination position and have it stay. The wrist cover for water, debris, and detergent resistance as well as the simple finger actuation system are included in this drawing as well.

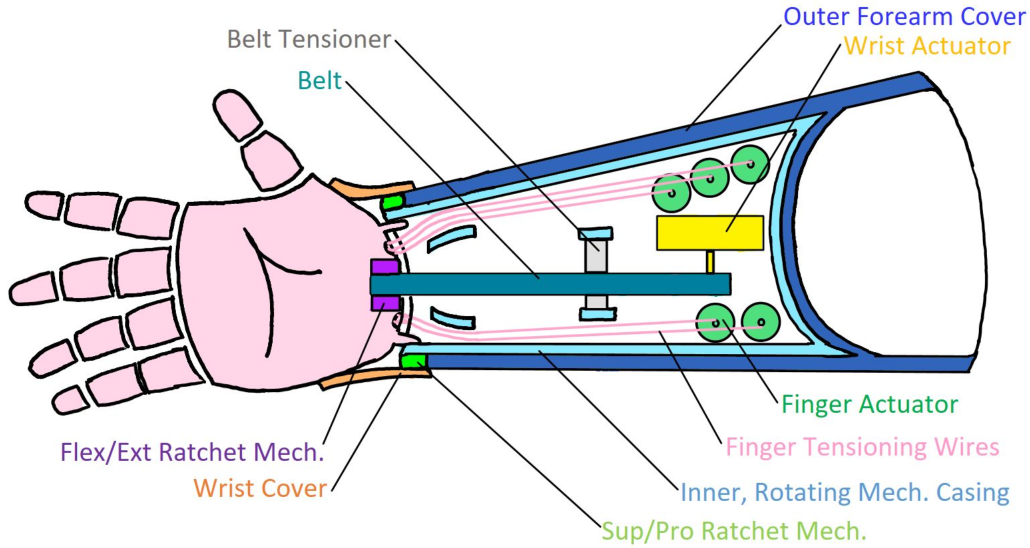



**Figure 9.** Labeled drawing showcasing the motor actuator with a belt for the active flexion/extension drive system. Drawing showcases the nested sleeve mechanism for passive pronation/supination, too.

### *5.4 Design 4: Motor Actuator and Rack and Pinion with a Belt Transmission System*

A labeled drawing showcasing the fourth of these ideas is shown below in Figure 10. This design highlights the active flexion/extension drive system that is actuated by a motor and uses a belt coupled with a rack and pinion as a transmission system. For this design, the hand is rigidly attached to a platform that is pivoted at the wrist. As the pinion moves along the rack, the wrist either flexes or extends to the desired position. Meanwhile, the use of the belt allows a majority of the device's weight to be kept proximal to the user, thereby reducing the amount of strain on their arm. This design also highlights the passive pronation/supination system that uses a nested sleeve mechanism. This nested sleeve mechanism consists of an inner casing that houses the mechanisms of the prosthesis and rotates within an outer forearm cover. Mechanical user input is required to use this passive pronation/supination motion. Additionally, this specific design of the nested sleeve mechanism uses a ratchet mechanism at the wrist that allows the user to rotate the wrist to the desired pronation/supination position and have it stay. The wrist cover for water, debris, and detergent resistance as well as the simple finger actuation system are included in this drawing as well.

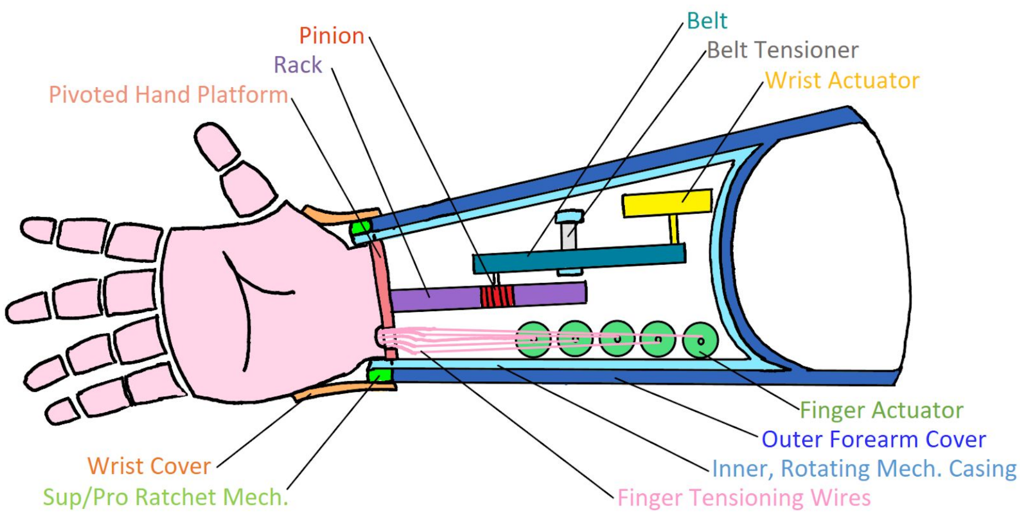



**Figure 10.** Labeled drawing showcasing the motor actuator with a belt coupled to a rack and pinion for the active flexion/extension drive system. Drawing showcases the nested sleeve mechanism for passive pronation/supination, too.

*5.5 Design 5: Linear Piezoelectric Actuators*

A labeled drawing showcasing the fifth of these ideas is shown below in Figure 11. This design highlights the active flexion/extension drive system that is actuated linear piezoelectric actuators. Piezoelectric actuators are solid state actuators that increase in length when a voltage is applied to them. For this design, the hand is rigidly attached to a platform that is pivoted at the wrist. A piezoelectric actuator is placed on either end of the pivot. When one of the piezoelectric actuators extends, the wrist flexes. Meanwhile, the wrist extends when the other piezoelectric actuator extends. This design also highlights the passive pronation/supination system that uses a nested sleeve mechanism. This nested sleeve mechanism consists of an inner casing that houses the mechanisms of the prosthesis and rotates within an outer forearm cover. Mechanical user input is required to use this passive pronation/supination motion. Additionally, this specific design of the sleeve mechanism uses a locking mechanism that allows the user to rotate the wrist to the desired pronation/supination position and lock its position. The wrist cover for water, debris, and detergent resistance as well as the simple finger actuation system are included in this drawing as well.

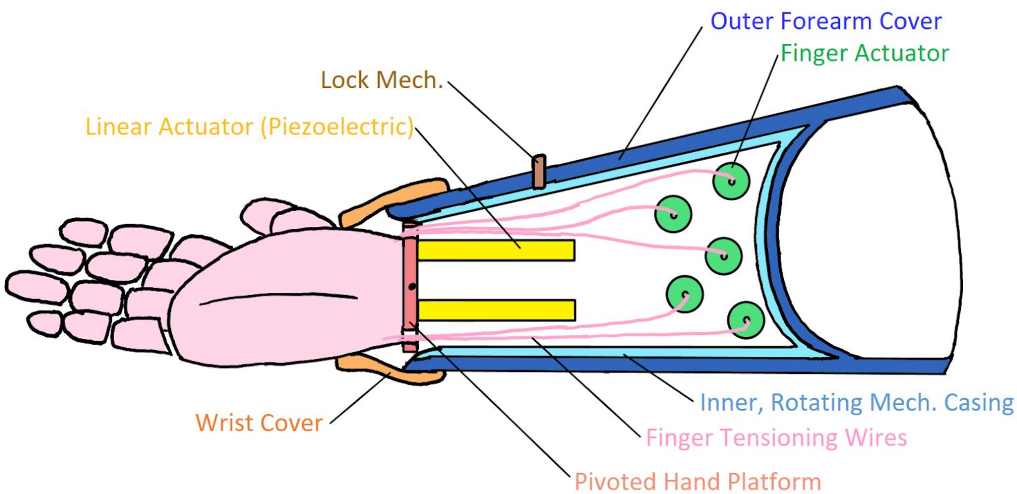



**Figure 11.** Labeled drawing showcasing linear piezoelectric actuators for the active flexion/extension drive system. Drawing showcases the nested sleeve mechanism for passive pronation/supination, too.

### *5.6 Design 6: Motor Actuators and Tensioning Wires*

A labeled drawing showcasing the sixth of these ideas is shown below in Figure 12. This design highlights the active flexion/extension drive system that is actuated by two motor actuators and tensioning wires. These tensioning wires loop through the base of the hand that is shaped like a ball. The wrist in this design is shaped in such a way to create a socket for the hand, which together creates a ball joint. When one of the actuators pulls the tensioning wires, the wrist flexes. Meanwhile, the wrist extends when the other actuator pulls the tensioning wires. This design also highlights the passive pronation/supination system that uses a nested sleeve mechanism. This nested sleeve mechanism consists of an inner casing that houses the mechanisms of the prosthesis and rotates within an outer forearm cover. Mechanical user input is required to use this passive pronation/supination motion. Additionally, this specific design of the nested sleeve mechanism uses a ratchet mechanism at the wrist that allows the user to rotate the wrist to the desired pronation/supination position and have it stay. The wrist cover for water, debris, and detergent resistance as well as the simple finger actuation system are included in this drawing as well.

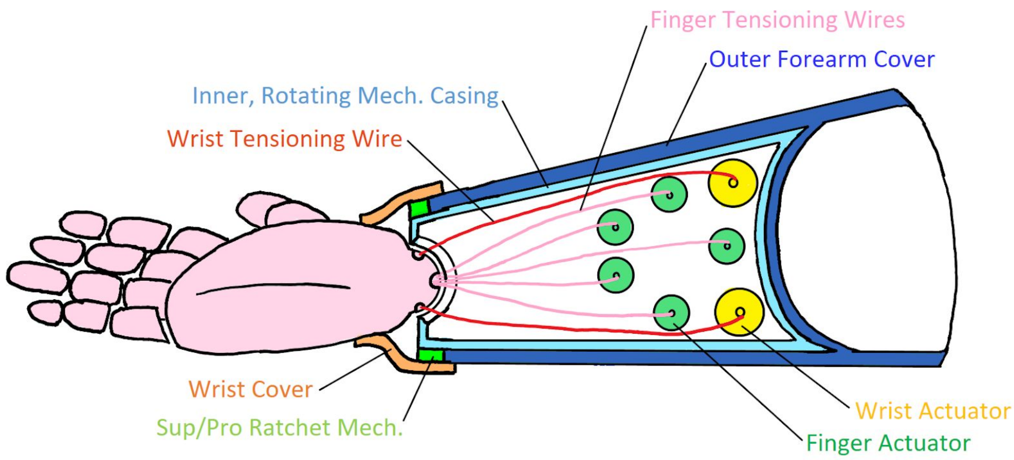



**Figure 12.** Labeled drawing showcasing motor actuators with tensioning wires for the active flexion/extension drive system. Drawing showcases the nested sleeve mechanism for passive pronation/supination, too.

### *5.7 Developed Power Source Designs*

This section provides labeled drawings for two of the three practical and promising power source designs from Section 4. The first of these is an embedded battery that is integrated into the prosthetic casing itself. This power source has a cover to protect the batteries and can be easily removed by the user whenever needed. Figure 13 below showcases this design.

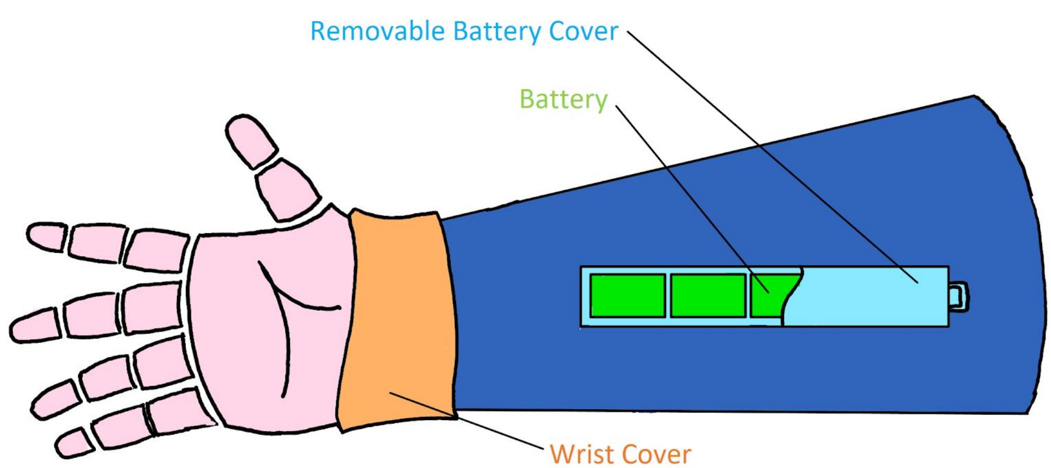



**Figure 13.** Labeled drawing showcasing embedded battery for the power source system.

Meanwhile, Figure 14 below showcases the second of these selected designs. This design uses a wearable battery pack that is secured to the user bicep. This design limits the weight contained within the prosthetic device and allows for more space to be allocated to other systems.

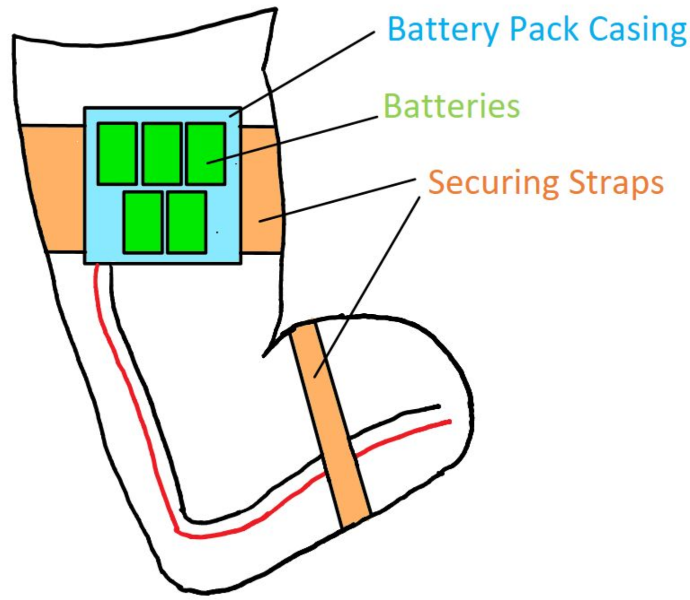



**Figure 14.** Labeled drawing showcasing a wearable battery pack for the power source system on a user's bicep with wires running to where the prosthesis would be.

# 6. Concept Evaluation and Selection

This section details the evaluation method used to assess the advantages and disadvantages of the designs that were generated in Section 4 and then further developed in Section 5. The practicality of these designs given the stakeholder requirements and engineering specifications for this project was also considered. To evaluate these designs, the project was broken down into subsystems: the active flexion/extension drive system, the passive pronation/supination system, and the power source system. The expanse of generated ideas were first evaluated individually through a "gut check" of whether these ideas were feasible and the readiness of the technology required to implement them. Pugh charts were then implemented to evaluate the concepts which passed this initial screening.

*6.1 Feasibility and Technological Readiness*

Evaluation of idea feasibility was primarily done based on team intuition. Some ideas, such as "Telekinesis" and "Hamsters Running on a Wheel" were immediately deemed to be not feasible by such a "gut check". Other ideas such as "Magnets" and "Solar powered" were deemed conditionally feasible, and were not initially ruled out without further investigation into existing technology and manufacturing. After parsing concepts down in this way, the ideas deemed feasible to some degree were evaluated on the basis of the technology needed to implement them. Questions explored in this stage of evaluation were the readiness of manufacturing techniques necessary, the availability of required materials, and the team's technological expertise. At this stage, concepts such as "Magnetic Flux Pinning" and "Nuclear Power" were ruled out on the readiness (or lack thereof) of the required technology. At the end of these first two stages of screening, there were six Flexion/Extension concepts, three Pronation/Supination concepts, and three Power Source concepts left to be evaluated via Pugh Chart.

*6.2 Flexion/Extension Drive System*

The six designs evaluated under the Flexion/Extension Drive System were “Worm Gear with Belt”, “Worm Gear with no Belt”, “Belt”, “Rack and Pinion”, “Linear Piezoelectric”, and “Tensioning Wires”, or Designs 1-6, respectively as described in Section 5. Designs were evaluated based on their cost, mass[2], location of Center of Mass (CoM), power efficiency, torque, backdrive resistance, and volume. For cost, mass, and volume, an ideal design would minimize these parameters. For power efficiency, torque, and backdrive resistance, an ideal design would maximize these parameters. For CoM, an ideal design would have a CoM located as far from the wrist as possible. Due to the high torque requirements of the device, maximum torque was given the largest weighting, followed by minimal backdrive and CoM away from the wrist.

In evaluating these concepts, “Worm Gear with Belt” (Design 1) was arbitrarily chosen as the reference design and assigned a value of 0 for all categories. The other five designs were given a score of 1, 0, or -1 depending on how they performed, or are assumed to perform, relative to Design 1. Due to the conceptual nature of these designs, some scores were assigned as an educated guess of how they may perform. As concept evaluation progresses, more information may come to light which could change the scores, as is expected in an iterative design process. Similarly, the weighting of each category, while currently reflective of the team’s opinion of relative importance, will also be subject to change as the project progresses and priorities shift. Table 3 below compiles the categories, weights, and scores of the designs.

[2] All designs excluding the Linear Piezoelectric were assumed to be actuated by an electric motor, and this mass was taken into account when assigning weighting.

**Table 5.** Pugh Chart evaluating the Flexion/Extension drive system concepts. The scores for "Worm Gear with Belt", "Worm Gear no Belt", and "Tensioning Wire" were all close enough to make the results inconclusive.

| Category | Weight | Worm Gear with Belt | Worm Gear w/o Belt | Belt | Rack and Pinion | Linear Piezoelectric | Tensioning Wires |
|---|---|---|---|---|---|---|---|
| **Minimal Cost** | 1 | 0 | 1 | 1 | 1 | -1 | 1 |
| **Minimal Mass** | 2 | 0 | 1 | 1 | 0 | -1 | 1 |
| **Maximum Distance of COM[3] from Wrist** | 4 | 0 | -1 | 0 | 0 | -1 | 0 |
| **Maximum Mechanica l Power Efficiency** | 2 | 0 | 1 | 1 | -1 | 0 | 1 |
| **Maximum Torque** | 5 | 0 | -1 | -1 | 0 | 1 | -1 |
| **Minimal Backdrive** | 4 | 0 | 0 | -1 | -1 | -1 | -1 |
| **Minimal Volume** | 3 | 0 | 1 | 0 | -1 | -1 | 1 |
| **Total** | | **0** | **-1** | **-4** | **-8** | **-9** | **-1** |

While "Worm Gear with Belt" (Design 1) received the highest score, the close tie between "Worm Gear no Belt"(Design 2) and "Tensioning Wires"(Design 6) leaves doubt as to whether a single best solution can be determined at this time.

### *6.3 Passive Pronation/Supination Drive System*

The three designs evaluated under the Passive Pronation/Supination Drive System were "Turntable", "Nesting Sleeves", and "Body Powered", as described in Section 5. Designs were evaluated based on their cost, mass, location of Center of Mass (CoM), power efficiency, volume, and ease of use. For cost, mass, and volume, an ideal design would minimize these parameters. For power efficiency and ease of use, an ideal design would maximize these parameters. For CoM, an ideal design would have a CoM

[3] COM - Center of Mass

located as far from the wrist as possible. As torque and backdrive are not relevant to a passive system, CoM away from the wrist was given the highest weighting..

In evaluating these concepts, “Turntable” was arbitrarily chosen as the reference design. As with the Flexion/Extension system, some scores were assigned as an educated guess of how they may perform, and may change with future iterations. Similarly, the weighting of each category is also subject to future change. Table 4 below compiles the categories, weights, and scores of the designs.

**Table 6.** Pugh Chart evaluating the Passive Pronation/Supination drive system concepts. The “Nesting Sleeve” concept is shown to be the optimal design.

| Category | Weight | Turntable | Nesting Sleeve | Body Powered |
|---|---|---|---|---|
| **Minimal Cost** | 1 | 0 | 0 | 1 |
| **Minimal Mass** | 2 | 0 | -1 | 1 |
| **Maximum Distance of COM[4] from Wrist** | 5 | 0 | 1 | 0 |
| **Maximum Mechanical Power Efficiency** | 3 | 0 | 1 | 1 |
| **Minimal Volume** | 5 | 0 | -1 | -1 |
| **Ease of Use** | 4 | 0 | 0 | -1 |
| **Total** | | **0** | **2** | **-3** |

This evaluation suggests that “Nesting Sleeve” is the optimal concept. The difference in scores, while still not large, promotes more confidence in the conclusion than with the Flexion/Extension system.

### *6.4 Power Source*

The three designs evaluated under the Power Source system were “Embedded Battery”, “Wearable Battery”, and “Hydraulics”, as described in Section 5. Designs were evaluated based on their cost, mass,

[4] COM - Center of Mass

power output, mobility, aesthetics, ease of maintenance, and volume. For cost, mass, and volume, an ideal design would minimize these parameters. For power output, mobility, aesthetics,and ease of maintenance, an ideal design would maximize these parameters. Due to the high power demands of the device, maximum power output was given the largest weighting, followed by ease of maintenance and maximum mobility.

In evaluating these concepts, “Embedded Battery” was arbitrarily chosen as the reference design. As with the previous systems, some scores were assigned as an educated guess of how they may perform, and may change with future iterations. Similarly, the weighting of each category is also subject to future change. Table 5 below compiles the categories, weights, and scores of the designs.

**Table 7.** Pugh Chart evaluating the Power Source concepts. The scores for “Embedded Battery” and “Wearable Battery” were close enough to make the results inconclusive.

| Category | Weight | Embedded Battery | Wearable Battery | Hydraulics |
|---|---|---|---|---|
| **Minimal Cost** | 1 | 0 | 0 | -1 |
| **Minimal Mass** | 2 | 0 | 1 | -1 |
| **Maximum Power Output** | 5 | 0 | 0 | 1 |
| **Maximum Mobility** | 4 | 0 | -1 | -1 |
| **Aesthetically Pleasing** | 3 | 0 | -1 | -1 |
| **Ease of Maintenance** | 4 | 0 | 1 | -1 |
| **Minimum Volume** | 2 | 0 | 1 | 1 |
| **Total** | | **0** | **1** | **-6** |

While “Wearable Battery” received the highest score, the close score of “Embedded Battery” leaves doubt as to whether a single best solution can be determined at this time.

# 7. Engineering Analysis

This section details the engineering analysis process used to determine the prosthetic wrist’s motion and load requirements. During concept generation, the aspects of the prosthetic wrist system were broken down into three categories: passive pronation/supination transmission system, active flexion/extension transmission system, and the flexion/extension actuation method. To determine the active flexion/extension transmission system and actuation method, an iterative process of calculations was used to determine the driving kinematics of the wrist, the best transmission system, and the best motor actuator. The iterative process employed for our calculations was provided to us by our stakeholder, who has extensive experience in the field of wearable robotics. The process is as follows:

1. Determining standard output requirements (torque and motion) of a wrist for activities of daily living, or ADLs.

2. Determining the transmission requirements based on the output requirements.

3. Converting the mechanical requirements gathered into electrical requirements (voltage and current) to select the necessary actuator

4. Determining the thermal output (heat dissipated) that will occur with the selected actuator and ensure that it is not great enough to be uncomfortable for the end user.

The criteria for determining the best transmission system and motor actuator were an acceptable efficiency, the ability to withstand the required torques and loads, and the ability to fit within the space constraints of the project.

*7.1 Standard Output Requirements for Performance of Activities of Daily Living*

To identify the output requirements of the wrist during the selected Activities of Daily Living, or ADLs (see section 3 for description of specific ADLs), the system was analyzed as a static rigid body. While the ADLs do require an angular velocity output of 2-3 rad/s, as found through experimental testing (see Appendix A), the acceleration was assumed to be minimal and thus was neglected. The hand was assessed at three angles relative to the horizontal axis of the wrist: Neutral (0°), Flexion (70°), and Extension (-40°). Figure 15 below illustrates the three positions in question.

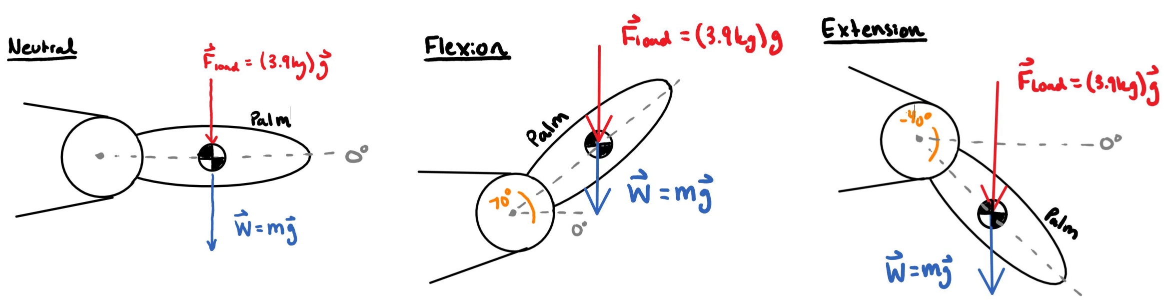



**Figure 15.** Free-body diagrams of the wrist and hand shown in neutral, flexion, and extension positions. (Left) Hand shown in neutral position. (Center) Hand shown to the fullest extent of flexion, 70° above the wrist axis. (Right) Hand shown to the fullest extent of extension, 40° below the wrist axis.

Under the assumption that the greatest torque would occur in our largest, adult male sized prosthesis, the calculations were performed assuming a hand weight, length, and center of mass (CoM) consistent with the average values found in an adult male [21]. As such, all computations assumed a hand length of 19.3 cm, a hand mass of 0.51 kg, and a CoM located 9.8 cm from the wrist. The load of 3.9 kg (the mass of a gallon of milk, as specified in the above ADLs) was then approximated as a point mass acting downwards on the CoM, perpendicular to the axis of the wrist. Table 8 below compiles the results of these three analyses. Although hand mass was estimated based on that of an adult human male rather than that of our true prosthetic hand, the calculation still holds as the 0.51 kg mass for the hand is the upper limit of the mass of the prosthetic device's hand.

**Table 7.** Compilation of computed output torque required by the wrist under maximum loading conditions. The neutral position, or 0°, resulted in the greatest torque required.

| Hand Position | Degree of Rotation | Resultant Torque (Nm) |
|---|---|---|
| Neutral | 0° | 4.3 |
| Flexion | 70° | 1.5 |
| Extension | -40° | 3.3 |

As shown above in Table 7, the greatest torque output of the wrist occurs when the hand is in neutral position, requiring a torque of 4.3 Nm.

*7.2 Transmission, Electrical, and Thermal Requirements*

The transmission and electrical requirements were found simultaneously through an iterative process. Voltage and current requirements for each motor were computed for a range of transmission ratios from 1 through 100. This range of gear ratios was chosen based on the available transmission components for the selected means of transmission and size constraints for the design. Essentially, available components that would achieve a gear ratio larger than 100 were too large for the desired size of the project. Thus, an ideal transmission ratio could be selected within this range for each motor by identifying the ratio that corresponded to the minimal current and voltage requirements. An ideal motor, as requested by Dr. Rouse, would run at 50 W or less. Motor voltage can be found through application of Kirchhoff's Voltage Law (KVL) around the motor circuit. Motor current in a DC Motor is directly proportional to the motor torque, which can be found through a moment balance. The equivalent circuit and simplified diagram of a DC motor are shown below in Figure 16.

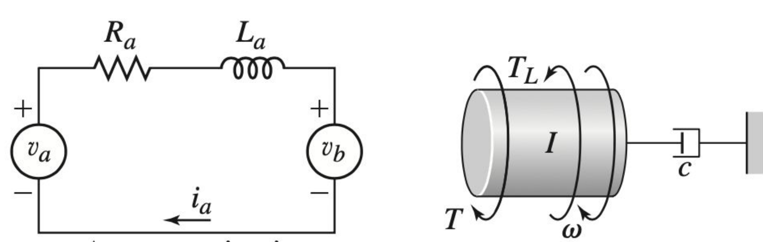



**Figure 16.** Equivalent circuit (left) and simplified diagram (right) of a DC motor[5] [22]. Analysis via Kirchhoff's Voltage Law and moment balance allows the derivation of equations for voltage and current, with the current proportional to torque through the torque constant.

[5] System Dynamics by William Palm, Third Edition

From Figure 16, Eq. 1 and 2 are derived:

$$V = R \cdot i + L\frac{di}{dt} + k_T\omega \qquad [22]\ (1)$$

$$k_T i = J_M\frac{d\omega}{dt} + b\omega + T_M \qquad [22]\ (2)$$

The variables $R$ (resistance), $L$ (inductance), $k_T$ (torque constant), $J_m$ (mass moment of inertia of the motor), and $b$ (damping) vary for each motor and are provided by the motor manufacturer. $T_M$ (motor torque) and $\omega$ (angular velocity) are the previously discussed output requirements, modified by the transmission ratio, N, and efficiency, $\eta$, as shown in Eq. 3-4:

$$T_M = T_L / N / \eta \qquad [23]\ (3)$$

$$\omega = \omega_w \cdot N \qquad [23]\ (4)$$

The efficiency of transmission components can be estimated to be between 85-90% [23]. However, assuming the worst case scenario, an efficiency of 85% was selected, and approximately 75 various DC motors, both brushed and brushless, were assessed. Figure 17 below shows the voltage and current requirements as a function of gear ratio for the set torque requirement for one of the tested motors.

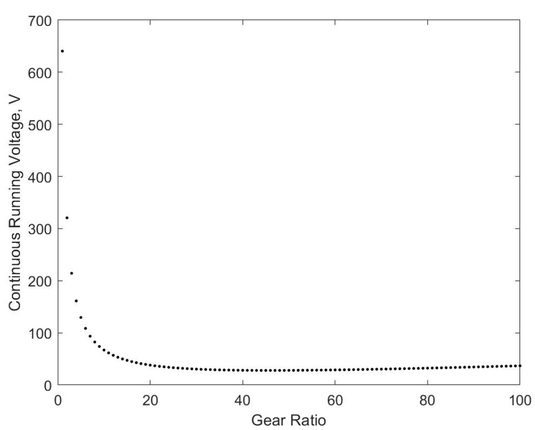



**Figure 17a.** Plot showcasing the required continuous running voltage for Maxon EC 45 Flat for the selected torque requirement as a function of gear ratio. The minimum required voltage is achieved at a gear ratio of 40.

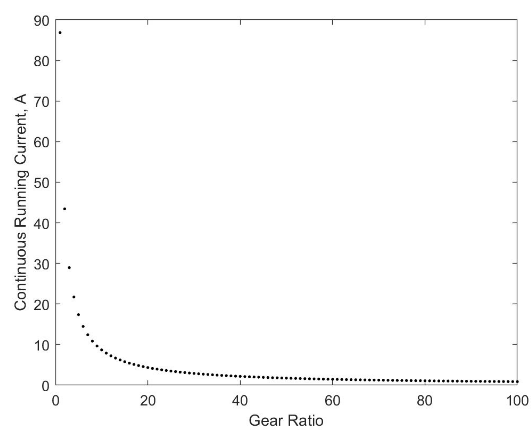



**Figure 17b.** Plot showcasing the required continuous running voltage for Maxon EC 45 Flat for the selected torque requirement as a function of gear ratio. The minimum required current is achieved at a gear ratio of 100.

After running this analysis of gear ratios, it was determined that the selected gear ratio should lie between 40 and 100 as to minimize the voltage and current requirements. Based on available transmission components and size constraints, a gear ratio of 80 was chosen. Using this gear ratio, the voltage and current requirements for each of the ~75 analyzed motors were compared using the following criteria: required power does not exceed the rated power of the motor, the required continuous current does not exceed 2 Amps for safety, and finally the required torque does not exceed the nominal torque of the motor. Thus, the best motor and transmission ratio combination was found to be the Maxon EC 45 Flat with a transmission ratio of 80, requiring a current of 0.90 A and a voltage of 31.0 V. This selected EC 45 Flat motor has a nominal voltage of 60 V and a power rating of 80 W. It is important to note that the criterion of required continuous current does not exceed 2 Amps was selected solely for this design iteration of the project. As prototyping is continued, the maximum allowable continuous current may increase as more safety measures are integrated into the design of the device.

With a motor and transmission ratio chosen, the thermal output was then assessed to confirm that the motor would not generate significant enough heat as to cause injury to the wearer. Thermal losses in the motor were evaluated using Eq. 5 below:

$$P_{loss} = i^2 R \qquad [23]\ (5)$$

The thermal loss was found to be 6.0 W, which was deemed minimal and therefore unlikely to result in any damage to the user or device.

# 8. Solution Development

*8.1 Subsystem Selection*

With the understanding of the mechanical and electrical output requirements needed, the three subsystem concepts were revisited (see Section 5). Preliminary modeling of the device with CAD allowed incorporation of the nesting sleeves concept for pronation/supination. This resulted in a clearer picture of the spatial constraints, immediately ruling out tensioning wires as a possibility for flexion/extension. Both remaining options, worm gear with and without a belt, would work with our spatial requirements; however, the addition of a belt allows for a more proximal motor position. Furthermore, it also allows for the sleeve diameter to taper in towards the wrist, reducing weight and more closely mimicking the natural curvature of the arm. As such, worm gear with a belt was chosen as the optimal flexion/extension mechanism. In addition to the flexion/extension mechanism, CAD modeling also lent to converging on a solution for power source. Similar to tensioning wires, spatial constraints do not allow for an embedded battery, and so a wearable battery was decided upon to power the motor. A sketch of the final design is provided below in Figure 18.

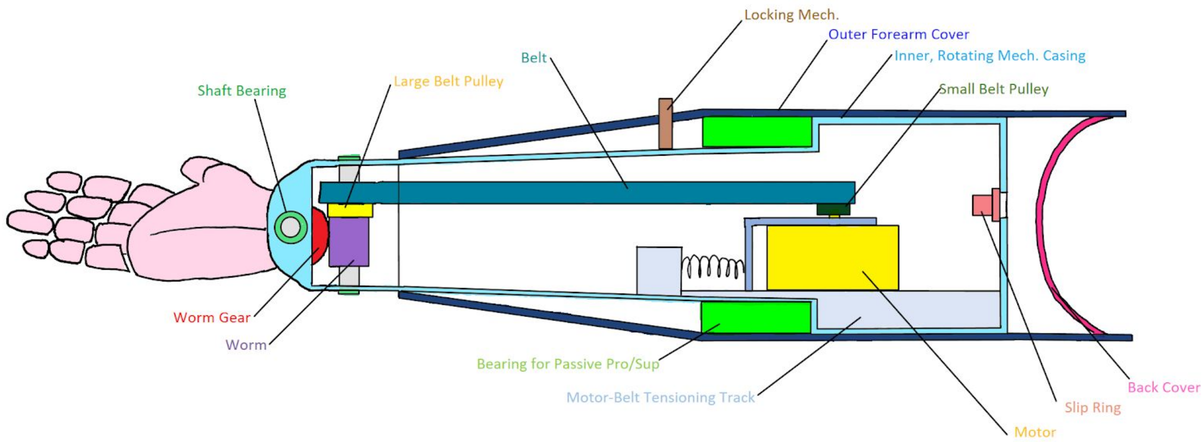



**Figure 18.** Labeled drawing showcasing the final design for the prosthetic device. Drawing showcases the nested sleeve mechanism for passive pronation/supination with a locking mechanism and the active flexion/extension belt with a worm gear system. The tensioning wires and finger actuators were changed into linear actuators within the hand that are not shown. Additionally, the water- and debris-proofing design is not included in the drawing above. Ultimately, this requirement will be achieved by covering the hand and wrist in a long, thick plastic glove that is clamped to the outer casing.

The drawing does not include the design for the hand actuation, which was changed to emulate the design of the Ada Hand by OpenBionics detailed further below in Section 8.3. The drawing also excludes the design for the water- and debris-proofing design, which is a long, thick plastic glove that covers both the hand and wrist. This glove is then clamped to the outer casing to create a seal.

*8.2 Transmission Component Selection*

To ensure the components of the transmission would be able to withstand the applied torque, multiple worms and worm gears were iterated through to assess the bending stress. The worm gear was assumed to be the point of failure, due to its weaker material. As such, the stress could be approximated with the Lewis Equation, shown below in Eq. 6:

$$\sigma = \frac{K_V W_T P}{F Y} \qquad [23]\ (6)$$

$W_T$ is the tangential load acting on the gear, approximated as the wrist torque divided by the pitch radius. $K_V$ (velocity factor), $P$ (Diametral Pitch), $F$ (Face Width) and $Y$ (Lewis Form Factor) are given by the manufacturer. Applying a wrist torque of 16.5 Nm[6], the bending stress in the chosen gear was found to be 202.4 MPa, less than the material's yield strength of 205 MPa.

A similar analysis was performed on the belt. Using the maximum torque applied on the wrist of 4.3N/m and tracking it back through the worm and worm gear, the maximum load the belt will need to carry is

[6] This assumes the user carries the 8 kg load with their wrist in the neutral position and their arm extended parallel to the ground, the worst-case scenario for static loading. Safety factor of 1.9 already included in this torque.

0.98 N. Multiplying by the safety factor of 1.9, this gives a max force of 1.9 N. The belt chosen is made of neoprene reinforced with fiberglass and is rated to handle a maximum load of 8.6 MN.

*8.3 Hand Subsystem*

Since the hand system was not the focus of this project, the team decided it would be best to use an open-source hand that was already available to the public. The design selected was the Ada V1.1 Hand by Open Bionics, shown in Figure 19. It was derived from the Dextrus created by the Open Hand Project whose mission is to “make robotic prosthetic hands more accessible to amputees” [24]. The Ada Hand was selected because it is a fully functioning design including 5 actuated fingers. Open Bionics has released the 3D print files, required tools, required components, and a completed printing/assembly guide [25][26]. Upon its initial release Open Bionics sold complete kits for the Ada hand, however they are no longer providing them. This will, unfortunately, result in the part acquisition process being less streamline. In addition, the Eagle schematic provided by Open Bionics would need to be used to CNC mill and wire a custom Almond PCB board [27]. Since the control scheme is not in the scope of this project that was not a limiting factor in the decision-making process. In future installments of this project, the hand subsystem can be refined, altered, and/or restarted at the discretion of the new design team.


**Figure 19.** The Ada Hand V1.1 by Open Bionics. The neutral finger positions (left) and all five fingers being actuated to grip a business card (right).

The assembly consists of four 3D printed components, nine M3 bolts, thirteen M3 threaded push insets, one meter of deep-sea fishing line (acting as tendons), five 12V PQ12 linear actuators, and a custom Arduino board. The palm of the hand should be printed in NinjaFlex PLA material, using around 200 grams of material and taking approximately twenty hours to print. The back cover and PCB trays could be printed in PLA or ABS material, using around 100 grams of material and taking approximately eight hours to print. The 3D print files are displayed in Figure 20 below. The completed assembly weighs approximately 0.47 kg and costs $437 for bulk materials, excluding the PCB board. The information used to inform the weight and cost values are presented in Appendix B.

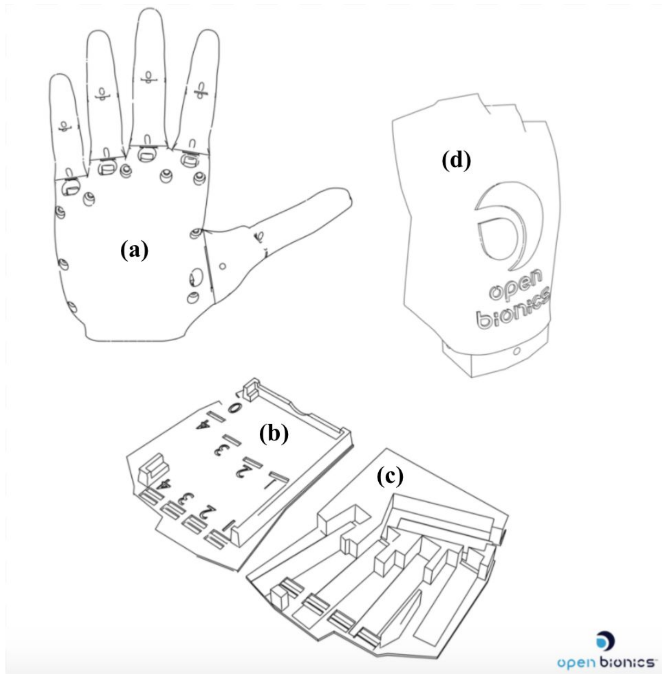



**Figure 20.** 3D printed parts: (a) palm, (b) upper PCB tray, (c) lower PCB tray, and (d) back cover. The front face of the palm and the fingers are all printed as one connected piece in flexible PLA material. This eliminates the need for additional components to control the motion of the finger joints and decreases the number of individual 3D printed parts. The lower PCB keeps the linear actuators in position and the upper PCB keeps the PCB board in position. The back cover encloses all internal components.

### *8.4 Additional Components and Open-Sourcing*

As one of our engineering specifications, open-sourcing played a significant role in the development of the project and the selection of its components. As such, all design decisions and rationale have been documented throughout the creation of this project. Additionally, the parts selected have all been commercially available and come from less than five suppliers. We also set a maximum total cost at $1000 or less. Therefore, the final prosthetic wrist design uses five suppliers/manufacturers: McMaster-Carr, KHK Gear Industry, Digi-Key Electronics, Amazon.com, Inc., and Maxon Group. This list of suppliers/manufacturers does not include the Actuonix Motion Devices, Inc. where the actuators for the hand can be purchased. Three of the components require additional machining to be done in order to have the finished part. These include the shaft for the worm gear, the shaft for the worm and pulley at the wrist, and the adapter coupler for the motor shaft to small pulley. The rest of the components within the design can be 3D printed. These components include: the outer casing, the inner sleeve, the motor mount, and the wrist reinforcement ring. Moving forward with the project, we will work to reduce the number of suppliers and the overall cost of the prosthetic device. We also would like to reduce the amount of machined parts, if at all possible.

*8.5 CAD Model for the Final Design*

This section details the CAD model for the final design for the prosthetic device. Figure 21 below provides an image of the overall CAD model without the Ada Hand included.

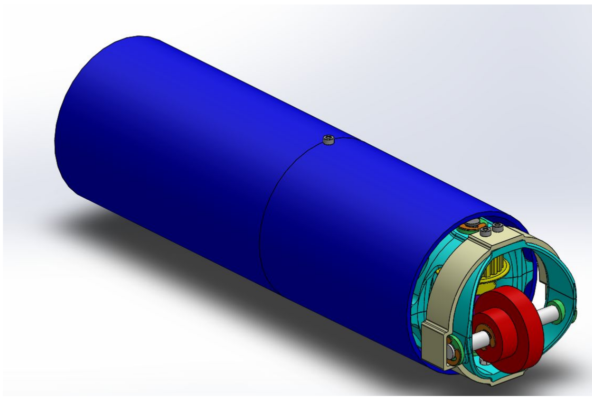


**Figure 21a.** Full overview of CAD model for the final design without the Ada Hand, which would be rigidly attached to the shaft holding the worm gear in red.

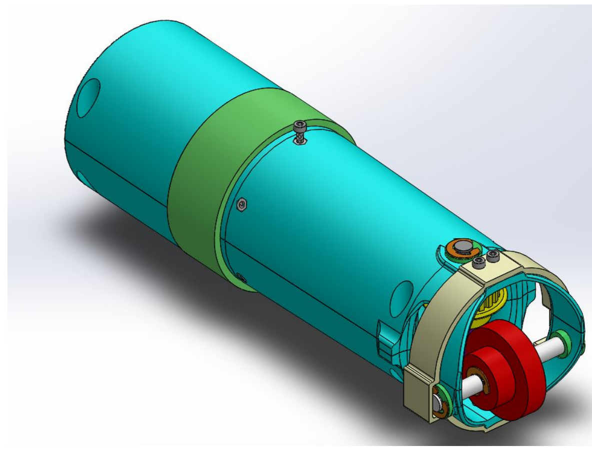


**Figure 21b.** Full overview of CAD model for the final design with the outer casing hidden. This image does not include the Ada Hand, which would be rigidly attached to the shaft holding the worm gear in red.

An isometric view of the full CAD model with the top inner sleeve mechanisms casing hidden is shown below in Figure 22.

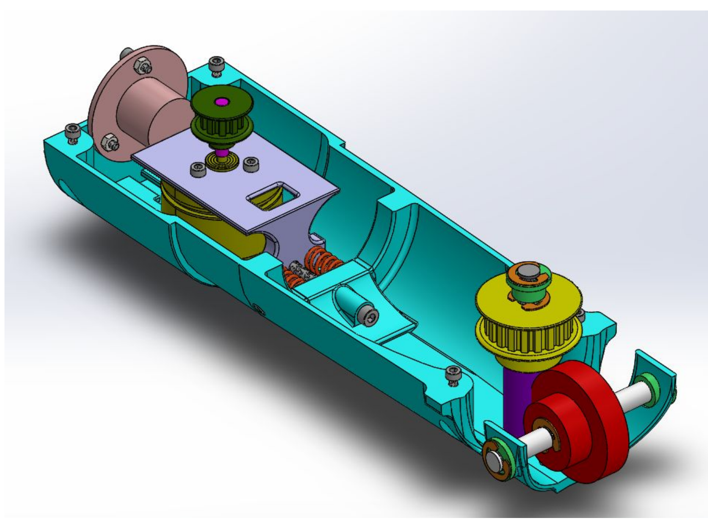


**Figure 22.** Isometric view of the CAD model without the Ada Hand with the top inner sleeve mechanisms casing hidden. The belt for the transmission system is also not not shown. However, it would connect the small pulley on the motor shaft (dark green) with the large pulley on the worm shaft (bright yellow).

As mentioned in Section 8, the final design of the prosthetic device consists of a brushless motor actuator that drives active flexion/extension via a two stage transmission system. The first stage of the transmission system is a timing belt, the second stage is a worm gear to help prevent backdrive. The worm gear of the system is rigidly attached to the hand subsystem, thereby causing flexion/extension as the gears rotate. Oil-embedded flanged bushings are included in the shaft design of the prosthetic device to allow for ease of rotation while external retaining ring clips are used to constrain axial movement of the gear shafts. A labeled diagram of the top view of the CAD model without the Ada Hand with the top inner sleeve mechanisms casing hidden is shown below in Figure 23.

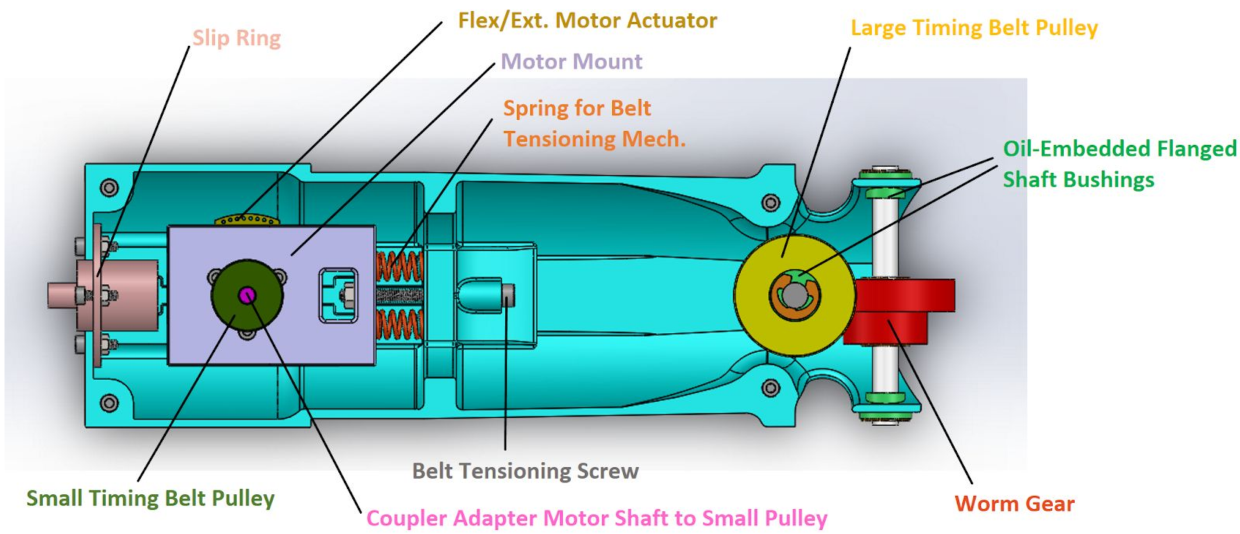



**Figure 23.** Labeled diagram of the top view of the CAD model without the Ada Hand. The top inner sleeve mechanism casing is hidden to show the inner mechanisms. The timing belt is also not shown.

The final design of the prosthetic device includes a passive pronation/supination mechanism, mentioned in Section 8. To achieve this passive motion, a large oil-embedded sleeve bushing is secured between the outer casing and the inner mechanism sleeve. This allows for an ease of rotation axially, or in the direction of pronation and supination. Plastic bumpers are included near the wrist of the inner mechanisms sleeve casings to prevent any moments that may occur due to the gap between the inner sleeve and the outer casing. These bumpers also prevent the outer casing from scraping against the ends of the worm shaft, thereby increasing the lifetime of the material. A basic locking mechanism is also included in the final design. There are six positions spaced 60° apart radially. Each of these positions has a nut that is press-fit and epoxied into the wall of the inner mechanisms casing. When the user pronates/supinates the wrist into the desired position, they can lock it in by screwing the locking screw into one these six nuts. Additionally, a slip ring is included at the back of the inner mechanism sleeve to prevent the wires that connect the flexion/extension motor to the external battery pack from tangling when the user pronates/supinates the wrist. A wrist reinforcing ring is also included in the final design of the prosthetic device. This ring helps secure the distal end of the prosthetic device together. This ring also aids in bearing some of the stresses the casings may experience during loading. Figure 24 below shows a labeled section view of the full CAD model, excluding the Ada Hand and timing belt below.

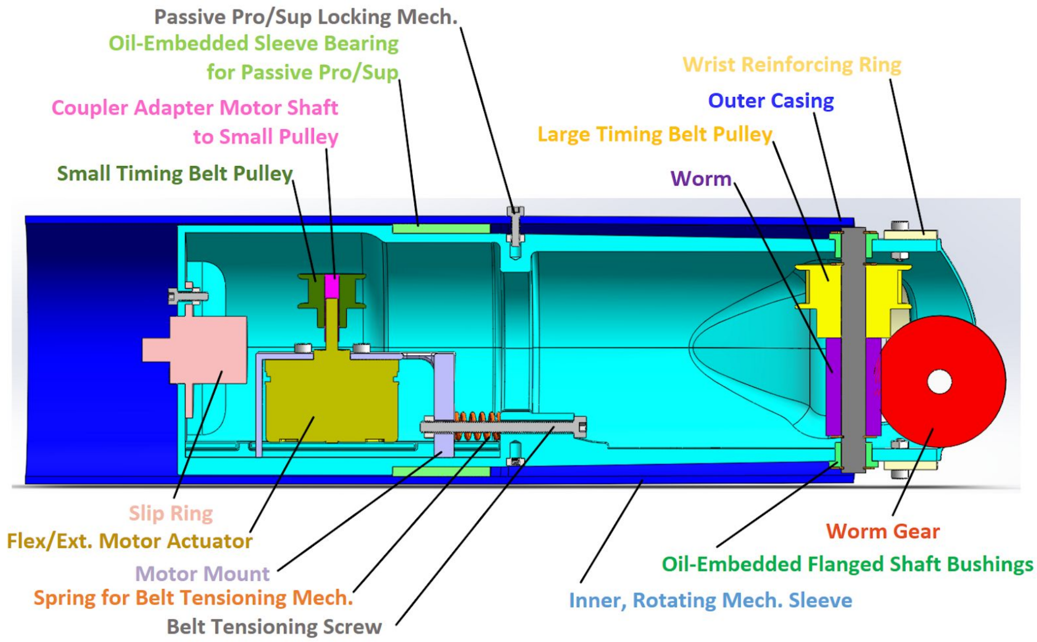



**Figure 24.** Labeled diagram of the full CAD section view for the prosthetic device, excluding the Ada Hand and timing belt.

Figure 25 below shows a simplified, labeled diagram of the gears meshing within the wrist. As the pulley is rotated by the timing belt, the worm rotates the worm gear, thereby allowing the hand, which is rigidly attached to the worm gear shaft, to flex/extend.

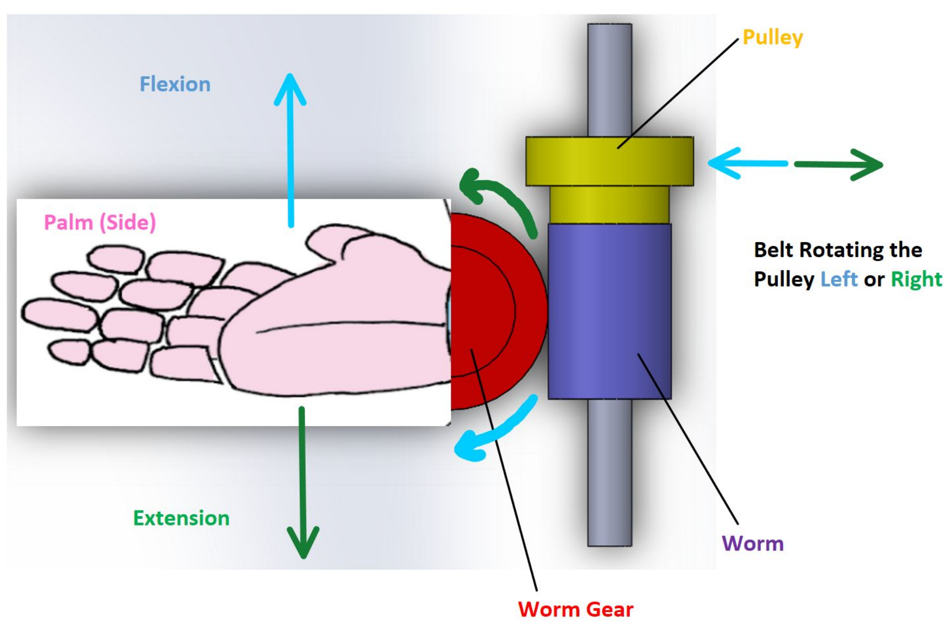



**Figure 25.** simplified, labeled diagram of the gears meshing within the wrist. Diagram shows how the hand will flex/extend based on the rotation of the belt.

To tension the belt of the transmission system, a linear tensioning mechanism was added into the design. The motor mount, which holds the motor, sits on a linear track. This mount interfaces with two compression springs. A tensioning screw runs through the motor mount and the lower inner mechanisms sleeve. As the screw is tightened, the springs are compressed further, which also loosens the belt as the pulleys are brought closer together. As the screw is loosened, the springs are compressed less, which also tightens the belt as the pulleys move further apart. A small window is included in the motor mount to allow for easy tool access to the tensioning screw's nut when the user wishes to adjust the tension on the belt. Alignment pegs are included in the lower inner mechanisms sleeve to help with installing the springs and keeping them straight. Urethane epoxy, which allows for metal to plastic bonding, is used to keep the springs in place. Figure 26 below offers a close up image of the belt tensioning mechanism.

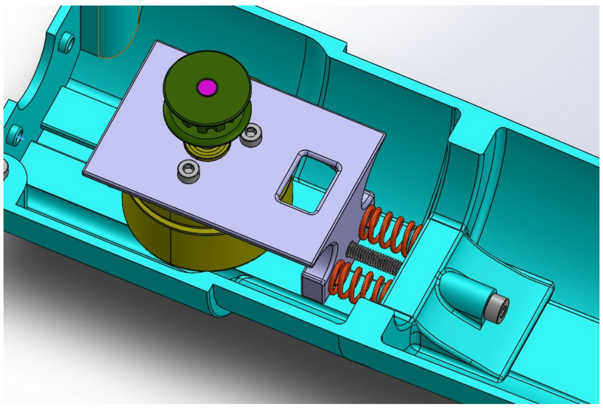


**Figure 26a.** Close up of the linear belt tensioning mechanism showcasing the motor mount interfacing with the two tension springs and the tensioning screw.

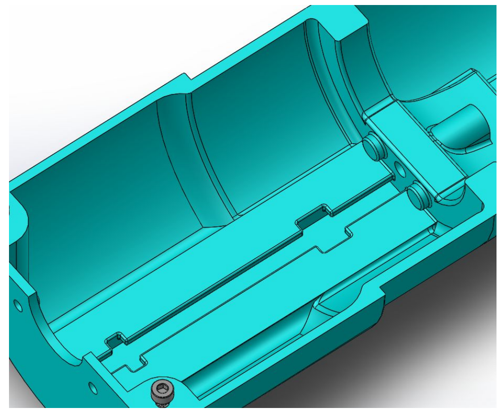


**Figure 26b.** Close up of the inner surface of the lower inner mechanisms sleeve showcasing the linear motor mount track and spring alignment pegs.

# 9. Risk Assessment

As a medical device, prostheses must be held to the highest safety standard for potential users. Throughout the design process, the team remained cognizant of the need to minimize risk to the greatest extent possible. Creation of a Failure Modes and Effects Analysis (FMEA) allowed for a deeper understanding of the broad range of risks associated with the design. The FMEA, which can be found in Appendix D, was created with the provided ME450 template. Severity, occurrence, and detection were rated from one to ten, in accordance with the scale outlined in Professor Cooper's lecture on Risk Assessment and Management [28].

The greatest risk identified by the FMEA is failure of the worm gear (RPN=48). This is a result of the potential for user application of loads greater than what is accounted for in the safety factor. Additionally, failure may occur from previously acceptable loads due to fatigue. Future actions to address this risk include durability testing, research into alternate gears, and user warning of maximum acceptable load.

Another component of concern is the inner sleeve (RPN=36). Failure of the inner sleeve at the distal end will result in partial-to-full loss of primary function (actuated flexion/extension). Additionally, failure may result in detachment of the hand. While the hand itself is lightweight, if this failure is to occur while the device is bearing weight, the resulting detachment poses risk of injury to the user. Verification via COMSOL modeling and prototype durability testing, as well as research into alternate gears, and user warning of maximum acceptable load are recommended to minimize this risk.

While not ruled a likely risk (RPN=30), the power source poses the greatest potential harm to the user. This is due to the 6A current the device will be providing, which is well above the threshold for fatal injury if transmitted to the human body [29]. However, due to low occurrence and probability of detection before release, this event is considered unlikely to occur. Proper precautions such as wire management, insulation, and user warning all mitigate the risk that the power source poses.

# 10. Next Step - Verification

The verification process was broken down into stakeholder requirements and engineering specifications. As previously discussed, the requirements in the future category were not verified. Due to the limitations on prototyping and testing, some secondary requirements were also not verifiable.The limitations on prototyping were due to a shortened timescale and limited access to prototyping facilities. Figure 27 below shows images of our first active prosthetic wrist prototype with a hand placeholder. The blue outer sleeve casing is not included in the completed image of the prototype, Figure 27.d., as it broke during assembly 3D print post-processing.

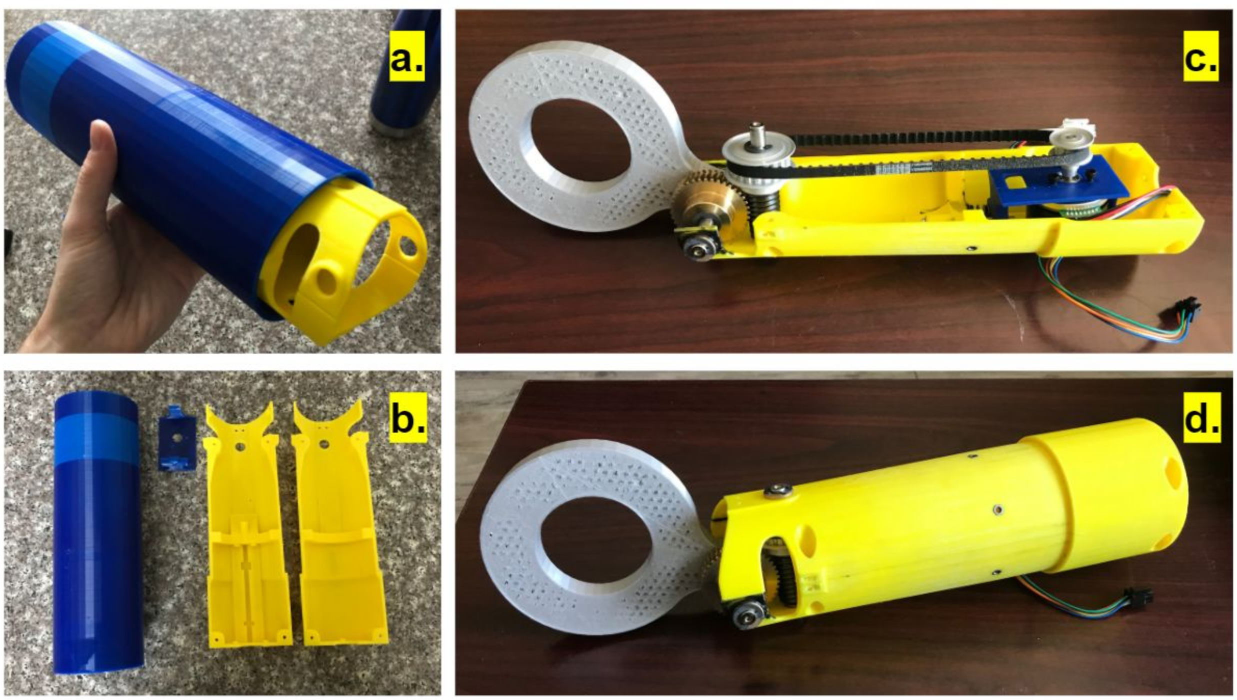



**Figure 27.** (a.) Inner and outer sleeve casings of the prototype nested in one another. (b.) 3D printed parts for the prototype laid out. These include from left to right the outer sleeve casing, the linear rail motor mount, and the two inner sleeve casings. (c.) The assembled prototype with a hand placeholder before being closed with a second inner casing. (d.) The assembled prototype without the outer casing.

*10.1 Mimics Human Wrist Movement*

To verify that the design meets this requirement, it will need to have the ability to perform pronation/supination movement when mechanically manipulated, rotate 70° in flexion and 40° in extension, as well as the ability to move at 2-3 rad/s. This was verified by using the motor and gear calculations mentioned in engineering analysis and solution development. In addition, a prototype was constructed and the motion was to be verified via real world testing. The BK Precision 1697 Switching Mode DC Regulated Power Supply (1-40VDC and 0-5A) and Escon 36/3, 4-Q Servocontroller for EC motors were used for prototype testing. The prototype was to be inspected visually for range of motion, and using video to determine the angular velocity. However, we were unable to properly run the motor driver test connectors we had available. The connectors available were loose on the driver pins, and therefore could not create an acceptable connection to allow for proper operation and current delivery. Instead of rotating, the motor would simply vibrate during testing. Though we were unable to verify the movement speed with the prototype, our driver and transmission calculations verified the required speed for our specifications are attainable. Figure 28 below depicts the prototype and the movement path, which was achieved by manually rotating the motor shaft.

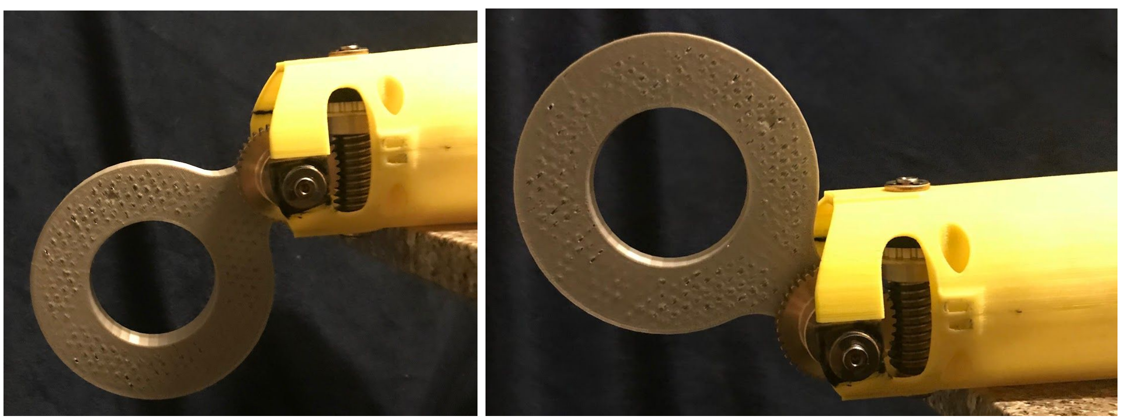


**Figure 28.** Start and end positions for the wrist prosthesis system. The start position is at -40 degrees extension, and the end position is 70 degrees in flexion.

*10.2 Load Bearing Capacity*

The specification for load bearing capacity is for the wrist to support ≥8 kg without failure. The course recommendations are for the prototype to not be tested to failure, so that there will be a presentable device after verification. As such, comsol models were created under the 8 kg static loading condition to determine if the 3D printed parts would be capable of sustaining the specified load. Figure 29 below shows the theoretical model of how the internal shell would respond to an axial load of 8 kg.

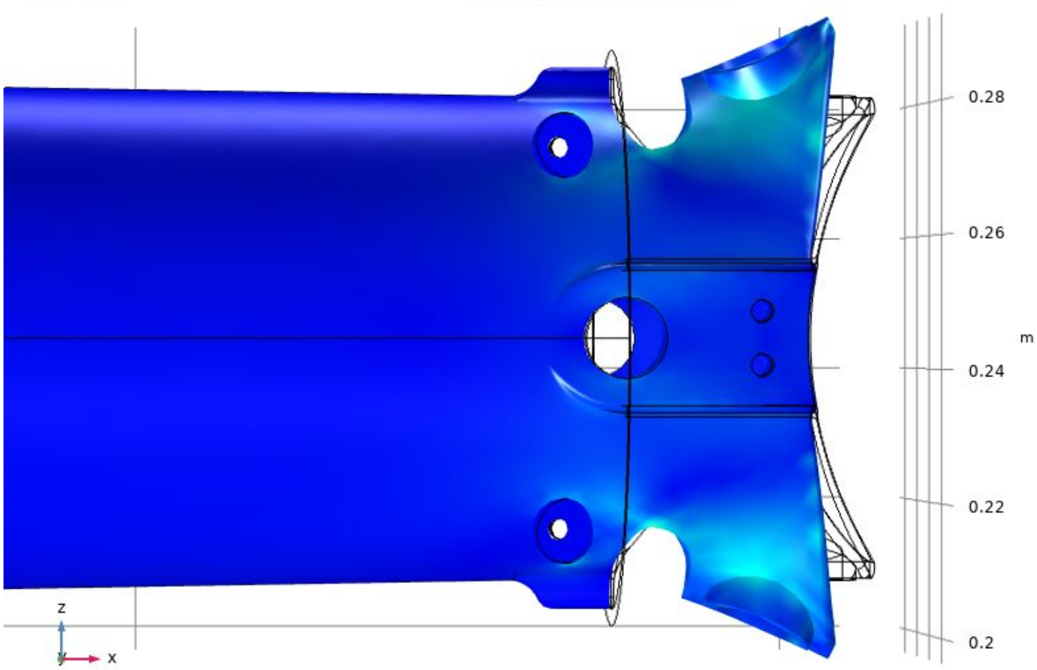



**Figure 29.** Comsol model for deformation of the inner shell under an axial load of 8 kg applied through the axis on which the hand would rotate.

As shown in Figure 29 above, the blue geometry is the shell after the load has been applied. The wireframe indicates the original geometry. The load is applied through the axis on which the hand would rotate. A similar model was also run for a vertical load, as if the arm was extended and the load was applied downward at the hand. Figure 30 below shows the geometry after the load was applied.

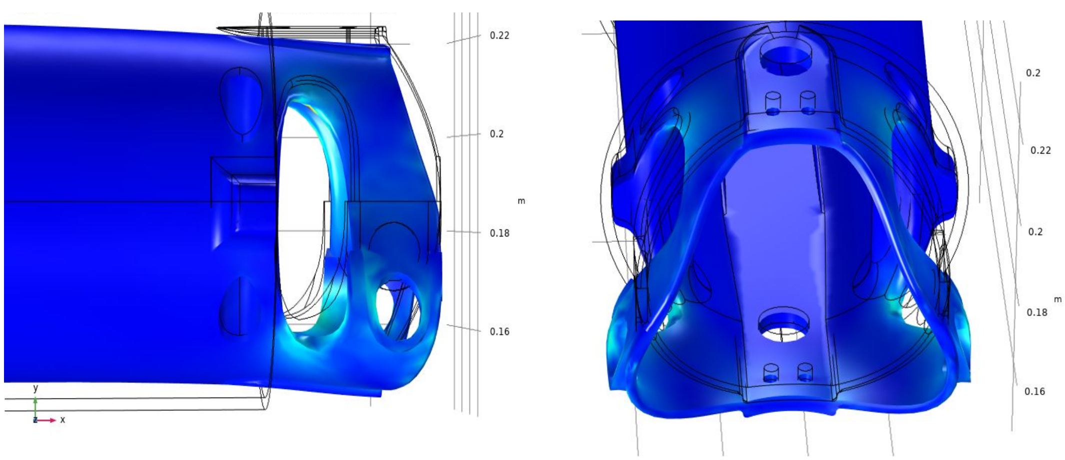



**Figure 30.** Side and front views of the comsol model of the inner shell after a vertical load of 8 kg was applied through the axis on which the hand would rotate.

As shown in both Figure 29 and Figure 30, significant deformation occurs under the maximum loading condition. In the given test cases, the internal shell of the arm is not strong enough to support the loads we are aiming for when constructed from ABS plastic. Note that while deformation would occur, it is likely that material failure and shattering would occur prior to such significant deformations being reached. The specific deformations shown in the figures are due to limitations of Comsol for modeling the behavior of the materials. Due to the failure of the shell when constructed from ABS, further investigation was done into alternative materials. Polycarbonate plastic was investigated as an alternative filament to 3D print due to it having a higher strength and lower density than ABS [30]. However, deformation still occurs within the thinner walls of the inner shell at the distal end of the arm. Further investigation to identify a suitable material as well as changes to the shell geometry will be conducted for future prototyping and testing.

*10.3 Lightweight and Integrated Power Source*

To meet the requirement of lightweight, the total device must have a mass of ≤ 2.26 kg. The mass of the assembled prototype is approximately 0.82 kg. It is important to note that due to limitations on time and the difficulties incurred by COVID-19, the prototype did not include a fully realized hand subsystem. With the mass of the hand system being approximately 0.47 kg this pushes the mass of the system beyond the 1 kg target with a total mass of 1.29 kg. However, the mass is still substantially below the average mass of a human arm, 2.26 kg [21]. In addition, budget and time constraints have also prevented the team from developing and/or securing a portable power source for the prosthetic device's design. Instead, a stationary power source was used to test and demonstrate the functionality of the prototype.

*10.4 Scalable, Water, Debris, and Detergent Resistant*

While the team only created one physical prototype, the specification of scalable to three sizes will be verified through creation of different sized models in CAD. These models will be scaled for different lengths of arms depending on user physiology. For the physical prototype, water, debris and detergent resistance will not be tested due to concerns about damage. The requirement has instead been met through purchase of a rubber glove with verified water, debris, and detergent resistant to go over the hand and wrist.

*10.5 Easy to Clean and Hand Functionality*

After assembly of the prototype was completed, a moist wipe was applied to the surface of the prototype to simulate cleaning. This process was timed, and took 2 minutes and 36 seconds to fully clean. This was less than the specification of 10 minutes. Due to the use of an open-source hand, the functionality of the hand has been verified and has been shown to meet the specifications as placeholders that open and close.

*10.6 Open-Source / Most Simple Design*

As the project has progressed, the team has been conscious of the specification that all design decisions and rationale must be documented. Alongside this report, meeting notes taken throughout the semester compile the discussions on design decisions made throughout the semester. Additionally, as discussed in Section 8.4, all parts of the device are commercially available and come from no more than five manufacturers. The total cost of all the parts do not exceed $1000.

# 11. Discussion and Recommendations

Given the constraints that were added onto this project due to COVID-19, such as shortening the semester,  making it an online course, and difficulties in manufacturing and material procurement, the team was only able to develop its first high-level prototype towards the end of the semester. In the future, a final design of the prosthesis that meets all of the chosen engineering specifications can be achieved with more iterations of advanced prototyping and testing.

This being said, a lot was learned from the prototype that was created. The first recommendation would be to increase the inner volume of both the inner and outer sleeves to account for shrinkage during the printing process of the ABS. The team did anticipate some shrinkage but due to the hollow cylindrical shape more shrinkage was experienced than initially designed for.

The next improvement that was realized from the prototype and from the static testing of the CAD model in Comsol was to make the inner shell of the design stronger. The team determined two ways to strengthen the inner shell. The first way would be to make the thickness of the shell larger and remove the windows that were included for lightweighting and set screw access. There is room spatially to accomplish this, and the mass of the prosthesis would still be less than that of a human arm after these changes. The other option is to use a stronger material than ABS. Although it would be more expensive, the team recommends using Onyx by Markforged, it is a micro carbon fiber filled nylon recommended by our stakeholder.

The final improvement to recommend would be to use a tensioning pinion to tension the belt instead of the compression spring on the linear guides. When talking with experts in the use of belt tensioners for similar functions, they recommended using a tensioning pinion. Further development and research will go into making this decision. The suggested advantages of this change would be making manufacturing and assembly easier.

There were also many strengths in the design. Rigorous calculations and iterations were involved in the selection of the motor. The team maintains that the motor selected is the optimal choice for the specified conditions under which it will be operating.

The team also believes that the mechanisms chosen and the gear train involved is the most effective design to transmit the necessary torque required to the distal end of the forearm while maintaining the bulk of the weight at the proximal end.

# 12. Conclusion

The project scope is focused on the performance of the wrist rather than the interface between the user and the prosthetic system. This project's goal is to add a single degree of freedom, DoF, to the wrist joint. The degree of freedom was chosen to be flexion and extension, as this is the optimal DoF for the investigated ADLs. Even though the wrist will be the focus of the project, a hand subsystem will be included in the project to ensure that that the volume of the hand systems is taken into consideration throughout the design and that the motion of the wrist joint is better displayed.

The team has completed the initial research and benchmarking procedures to ensure that there is a need for improved bionic prostheses. Based on this research, and input from the stakeholder, Dr. Elliot Rouse, the team has compiled and ordered a list of requirements for the project. The requirements were converted into a set of quantifiable engineering specifications based on the benchmarking and research conducted. In addition, these specifications are also created based on data for activities of daily living, ADLs, that end users of the prosthetic system typically undertake.

The team has completed concept generation activities. A number of techniques were used to generate ideas including individual brainstorming, morphological analysis, and design heuristic cards. The ideas were then evaluated using pugh charts categorized by the active flexion/extension drive system, the passive pronation/supination drive system, and the power source. Based on the pugh charts several concepts were determined to be the most effective. For the flexion/extension drive system a worm gear with a belt, worm gear without a belt, and tensioning wires were determined to be equally viable solutions. For the pronation/supination drive system a nesting sleeve was determined to be the best solution. For the power source an embedded battery or wearable battery were determined to be equally viable solutions.

After selecting the best concept, we conducted engineering analyses to develop our final design solution. The engineering analyses that were performed helped to select the transmission ratio, components, and electrical requirements of the final design solution based on the engineering specifications we selected. The components that were specifically investigated were the belt and gears that compose the transmission system as well as the motor actuator that drives active flexion/extension. These components were analyzed using equations such as the electromechanical equations from MECHENG 350 and 360 for our motor as well as the Lewis equation for our gear strength. Using the final generated design solution, a complete CAD model was created.

Ultimately, prototyping and simulation software were employed to verify that our final generated design solution fulfilled our specified requirements. Due to limitations on time and other difficulties resulting from COVID-19, the prototype did not include a fully realized hand subsystem. Through our testing and simulation, we verified that the current design did or had the ability to fulfill its engineering specifications, excluding load bearing capacity and integrated power source. Additionally, the idealized goal of having the arm weigh ≤1 kg for our lightweight engineering specification was not met. However, the prototype still met the lightweight engineering specification as it weighed less than that of an average, adult human forearm. Although not all of our specified requirements were met with our current design, further design iterations will allow us to develop a prototype that achieves all of these requirements.

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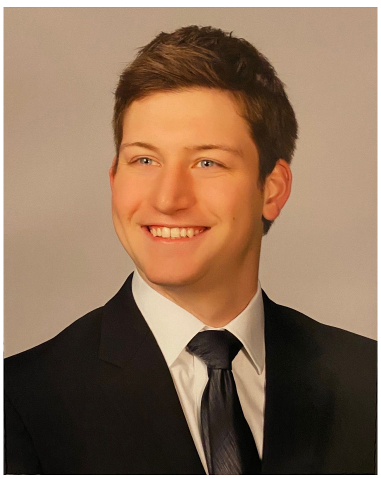

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# Appendices

## Appendix A: Testing Data for ADL range of motion & speed

The following table contains the data from testing to determine the angular speed for the selected ADLs. Testing was performed using video recordings of the motion and visual inspection by the engineers. The maximum change in angle is the greatest magnitude of change that the wrist experienced, measured in degrees. For instance, if the wrist starts off at 20 degrees of flexion, and proceeds to 40 degrees of flexion, the maximum change in angle is 20 degrees. These methodologies were the same ones employed by Jessop, David M, and Matthew T G Pain [19].

| ADL | Maximum change in angle (degrees) | Time for motion (seconds) | Average Angular Speed (degrees/second) |
|---|---|---|---|
| Eating | 70 | 1.1 | 63.6 |
| Brushing Teeth | 20 | .35 | 57.1 |
| Combing Hair | 70 | .5 | 140.0 |
| Washing Hands | 90 | 1.2 | 75 |
| Applying Lotion/Deodorant | 40 | .4 | 100 |
| Getting Dressed | 30 | .2 | 150 |
| Carrying Groceries | 5 | 1 | 5 |

## Appendix B: Ada Hand Assembly

The following section presents a sample parts list for the Ada Hand by Open Bionic. The vendors are just one source, most parts can be purchased from multiple places. The prices used in the total calculation are for the bulk purchase of the part and the mass is for the parts actually used in the assembly.

**Table B.1:** 3D printed Parts

| **Part** | **Material** | **Spool Cost** | **Cost of Material Used** | **Mass (kg)** |
|---|---|---|---|---|
| Palm | Ninja flex | $45.00 | $18.00 | 0.200 |
| Back cover | | | | |
| PCB tray upper | PLA or ABS | $23.00 | $4.50 | 0.100 |
| PCB tray lower | | | | |

**Table B.2:** Parts Purchased from External Vendors

| Part | Quantity | Vendor | Cost | Total Mass (kg) |
|---|---|---|---|---|
| M3 bolts (6mm length) | 9 | Home Depot | $1.68 | 0.041 |
| M3 threaded push inserts | 13 | Grainger | $14.70 | 0.004 |
| 0.7mm tendon string | 1 spool | Walmart | $14.49 | 0.036 |
| PQ12-30-12-P linear actuators 12V | 5 | Actuonix Motion Devices Inc. | $325 | 0.075 |
| Micro gel fingertip grips | 5 | Amazon | $10 | 0.012 |
| Super glue | 1 | Walmart | $2.50 | Negligible |

# Appendix C: Bill of Materials

The following section shows the bill of materials used in the assembly.

| Part No. | Part Title | Material | Descriptio n(s) | Supplier | Part Number (w/ link) | Quantity | Unit Price |
|---|---|---|---|---|---|---|---|
| 1 | Flex/Ext Brushless Motor | N/A | EC 45 flat ⌀42.8 mm, brushless, 80 W, 60V with Hall sensors and cable (Includes $44.63 of international shipping) | Maxon | EC 45 Flat brushless motor | 1 | $240.13 |
| 2 | Elegoo Uno microcontroller board kit | N/A | Elegoo Uno microcontroller board kit that includes circuit components such as breadboards and special components for dealing | Amazon | Elegoo Uno Kit | 1 | $39.21 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | with high currents and voltages | | | | |
| 3 | Pro/Sup Oil-Embeded Bronze Bearing | | 3-1/4" bronze sleeve bearing for passive pro/sup | McMaster-Carr | 6391K852 | 1 | $15.40 |
| 4 | Shaft Oil-Embeded Bronze Bearing | Bronze w/oil | Flanged bronze bearings for 8mm gear shafts | McMaster-Carr | 6659K677 | 4 | $2.35 |
| 5 | Large Timing Belt Pulley | Anodized Aluminum | 20 tooth corrosion-resistant timing belt pulley | McMaster-Carr | 1277N718 | 1 | $13.22 |
| 6 | Small Timing Belt Pulley | Anodized Aluminum | 10 tooth corrosion-resistant timing belt pulley | McMaster-Carr | 1277N11 | 1 | $11.11 |
| 7 | Shaft External Retaining Ring | Black Phosphate 1060-1090 Spring Steel | E-clips for gear shafts. Comes in packs of 50 | McMaster-Carr | 99178A105 | 1 | $6.00 |
| 8 | Gear Shaft Stock | 316 Stainless Steel | Stainless Steel, 8 mm diameter, 200 mm long rotary shaft stock | McMaster-Carr | 1265K64 | 1 | $20.55 |
| 9 | Socket Head Screws | Black-Oxide Alloy Steel | M3 x 10 mm socket head screws. Comes in packs of 100 | McMaster-Carr | 91290A115 | 1 | $7.62 |
| 10 | Steel Hex Nut | Steel | M3 nuts. Comes in packs of 100 | McMaster-Carr | 90592A085 | 1 | $0.88 |
| 11 | Belt Tensioning | Music-Wire Steel | 15 mm long, compression | Mcmaster-Carr | 94125K612 | 1 | $10.36 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Springs | | springs. Comes in packs of 5 | | | | |
| 12 | Timing Belt | Neoprene with fiberglass reinforcing | 18" long x 1/4" thick neoprene timing belt | Mcmaster-Carr | 6484K128 | 1 | $5.07 |
| 13 | Urethane Adhesive | Urethane | Structural adhesive that allows for the bonding of plastic to metal | Mcmaster-Carr | 7605A6 | 1 | $7.46 |
| 14 | Motor Wiring Connector 1 | N/A | 6 pin, 3 mm, male connector | Digi-Key | 430200601 | 1 | $0.45 |
| 15 | Motor Wiring Connector 2 | N/A | 4 pin, panel mount, male connector | Digi-Key | 39012041 | 1 | $0.41 |
| 16 | Slip Ring | N/A | 12 wire slip ring, allows 2 amps of current per ring | Digi-Key | ROB-13065 | 1 | $19.95 |
| 17 | Worm | S45C | Worm for flex/ext | KHK | SWG1-R1 | 1 | $63.60 |
| 18 | Worm Gear | CAC702 | Worm gear for flex/ext | KHK | AG1-40R1 | 1 | $52.67 |
| 19 | Motor Driver | N/A | ESCON 36/3 EC, 4-Q Servocontroller for EC motors, 2.7/9 A, 10 - 36 VDC | Maxon | 414533 | 1 | $250.13 |

# Appendix D: Failure Modes and Effects Analysis (FMEA)

| Component | Function | Potential Failure Mode | Potential Effect of Failure Mode | Severity | Potential Cause of Failure | Occurrence | Current Controls | Detection | RPN | Recommended Action |
|---|---|---|---|---|---|---|---|---|---|---|
| Inner Sleeve | Contains transmission system and motor, supports hand system | Severe deformity at distal end | Flexion/ extension motion cannot occur | 8 | Fatigue failure | 2 | Material analysis | 2 | 32 | Research materials further, conduct durability testing |
| | | Fracture at distal end | Hand falls detaches from sleeve and injures user | 9 | Fatigue failure | 2 | Material analysis | 2 | 36 | Research materials further, conduct durability testing |
| Outer Sleeve | Supports pronation/ supination rotation | Fracture and/or severe deformity | Prevents pronation/ supination | 6 | Fatigue failure | 3 | Material analysis | 2 | 36 | None |
| Motor | Actuates flexion/ extension motion | Shaft failure | Transmission system cannot be powered | 8 | Fatigue failure; deformation | 1 | Test motor | 1 | 8 | None |
| | | Electrical failure | Transmission system cannot be powered | 8 | Manufacturi ng error | 1 | Test motor | 1 | 8 | None |
| Breadboard | Interfaces with motor to control velocity and torque | Short or open circuit | Motor is not powered | 8 | Improper wiring; wiring not properly secured | 4 | Thorough assembly inspection , testing | 1 | 32 | None |
| Power Source | Supplies power to motor and breadboard | Short or open circuit | Injury to user | 10 | Improper wiring; wiring not properly secured | 3 | Thorough assembly inspection | 1 | 30 | None |
| Belt Tensioning Springs | Prevents belt from developing slack | Loss of stiffness | Reduced ability of belt to transmit torque | 4 | Fatigue failure; deformation | 2 | Material analysis | 3 | 24 | None |
| Timing Belt | Transmits torque from motor to worm | Snap | Belt cannot transmit torque | 8 | Fracture | 3 | Material analysis | 2 | 48 | Research materials further, conduct durability testing |
| Worm Gear | Transmits torque from worm to hand | Fracture and/or severe deformity | Gear cannot transmit torque | 8 | Fatigue failure | 3 | Material analysis | 2 | 48 | Research materials further, conduct durability testing |

# Appendix E: Supplemental Learning Modules

**Engineering Standards**

The team performed industry benchmarking to help inform design specifications. This insured that our design was comparable and competitive among industry standards. We experienced difficulty finding upper limb prosthetic standards, so the ISO 10328:2016 standards for lower limb prosthetics were used for the durability specification. The safety range for voltage and current in contact with the human body were taken into account when making motor selection and will be used in the future to determine the required electrical insulation. The team hopes that in the future, ISO will have published standards for upper limbs to give concrete guidelines for the design specifications for durability and use.

**Engineering Inclusivity**

The team tried to practice inclusive design as much as the current social situation allowed. We had biweekly meetings with our stakeholder who has years of experience with lower limb bionic prosthetics. We used his personal experience with amputees to inform the requirements patients look for in a prosthetic and find most important. Our stakeholder and team stakeholder contact attempted to get into communication with a prothetician, but were unsuccessful. The team hoped to obtain feedback from medical professionals who work directly with amputees and with patients who use or want to use bionic prosthetics. Our design is based on the average male arm. However, a requirement of the design is that it can be scaled to at least three sizes. This is to accommodate for women and children sizes. In order to make it more inclusive we could also scale to sizes that are larger or smaller than average.

**Environmental Context Assessment**

Our final design meets both criteria to be deemed environmentally sustainable. It is addressing the unmet need of actuated wrist motion in bionic prosthetics. Losing a limb can significantly impact people's way of life and ability to fulfill daily activities. When compared to able-bodied individuals, amputees experience a significant restriction in mobility and loss of competency performing activities of daily living (ADLs). A bionic prosthetic can help restore mobility and allow wearers to perform ADLs with more ease. In addition we plan for our design to be open sourced and have a total cost of no more than $1000. This will make bionic prosthetics more accessible to amputees with lower disposable incomes.

We do not foresee any potential negative implications of our design that would overshadow the benefits. By 3D printing parts we reduced the amount of waste produced in the manufacturing process compared to if we machined parts from metal stock. After manufacturing the design would only use electricity to recharge the power source and will not emit any pollutants into the environment.

**Social Context Assessment**
Our design is likely to be adopted and self sustaining in the market. Since it will be open sourced users can purchase, manufacture, and assemble all components on their own if they have all the necessary equipment. If they do not have access to the equipment needed or do not want to assemble the device themselves they should be able to easily outsource the work. We do not foresee the design being so successful that the planet is worse off given the need for the device is based on people losing limbs. The design should be resilient to disruptions in business as usual since it will be significantly cheaper than prosthetics with comparable function and can be fully produced by the user. For these reasons we believe our design is socially sustainable.

**Ethical Decision Making**
In our decision making process the team practiced duty and virtue ethics. We made decisions based on what was best for the user rather than what was easiest for use. When designing user safety was a top priority. For Example, after the desired motor was identified current and voltage analysis were performed to determine if  it was safe to run the motor in close contact with a person. We also followed the ASME's ethics standards and the University's honor code. All reported all values honesty, even when it resulted in a major design change.