Next Gen Wearable Robotics

A Major Qualifying Project Report:
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Abstract

The overall goal of this project was to create a practical prosthetic wrist and gripper. The motivations behind this project were to further develop the applications of the HydroMuscle and highlight opportunities for improvement within the field of commercial transradial prosthetics by designing a prosthetic device with compliant motion actuated by HydroMuscles. This project consisted of the design of a wrist joint with two rotational degrees of freedom, a gripper with HydroMuscle actuated fingers capable of basic grasping tasks, a compact pump actuation system to convert rotational movement from a small motor to linear expansion of a HydroMuscle, and the development of controls and feedback to control the actuation.

Acknowledgements

We would like to thank our primary advisor, Professor Marko Popovic for his guidance throughout this year-long project. Especially highlighting his advice and support through the tough end of the year.

We would also like to thank Matthew Bowers, Ellen Clarrissimeaux, Julia D'Agostino, & the rest of Popovic Labs for their support and advice bringing this project to fruition.

Executive Summary

Many prosthetics are available for patients with transradial amputations, giving patients options with varying capabilities and functions at the hand. However, most commercial prosthetics include only one, if any, of the human natural wrist motions, due to multiple factors. The motivation of this project was to create a HydroMuscle actuated prosthetic wrist, which would provide compliant motion in a lightweight, compact, closed system. The wrist joint was designed to have two degrees of freedom. The gripper was designed to be integrated with the wrist and complete simple tasks, and code was developed to control the motors and process sensor feedback. This paper will cover the research, experiments, and iterations of the aforementioned components.

HydroMuscles are artificial muscles developed in WPI Popovic labs that pair elasticity with hydraulic or pneumatic position control. They create a linear tensile force with a fluid response to impact or strain. HydroMuscles have many benefits as they are efficient, lightweight, soft (compliant), create biologically inspired motion, and made out of inexpensive, readily available materials. Previous projects have used HydroMuscles of varying sizes in a multitude of applications relating to human muscle assistance and replicating muscle function.

The wrist was designed to allow flexion-extension and radial-ulnar rotations with limits inspired by human biology. The gripper design was inspired by human biology, with the passive capability to conform to different object geometries due to the elasticity of the HydroMuscles. These three degrees of freedom were intended to be controlled independently, with one HydroMuscle actuation system for each. This necessitated a novel approach to actuate the system due to our size and volume constraints. The Corkscrew Actuator is a compact means of using motor rotation to move the volume of fluid, controlling the HydroMuscle linear extension. Initial

inspiration came from a syringe, but the rotational motor saves space and the inner bag prevents the need for a high-friction water-tight seal. Control of the system was achieved using an Arduino Nano and two DC motor controllers. The feedback loop was created using the data from a hall effect sensor on the motor and a force sensor placed in the fingertips. To improve the control of the motor a PID (Proportional, Integral, Derivative) system. The functional goals for our project were as follows:

I. Our primary goal was to have a completely enclosed system contained to the forearm of the amputee. The total weight goal was approximately 3.0 pounds, the wrist would only take 3 inches of length from the tip of the ulna bone, and the circumference of the system would be approximately 9.5 inches wide.

II. The wrist would flex and extend 155 degrees, and the radial and ulnar motion was 50 degrees.

III. The hand/gripper had one actuated degree of freedom with the ability to grasp an object with a circumference of approximately 4.7 inches wide.

IV. The system would be controlled using a sensor feedback loop to control grip force and the position of the plunger. The system would also be programmed to pick up and move objects from one location to another to prove motion capabilities.

V. Post outbreak, the goal for the team was to show each component worked on its own.

The concern of patient control of the device, through means such as electromyographic (EMG) signals as mentioned in the background, was beyond the scope of this project. Unfortunately, due to the COVID-19 outbreak we were unable to finish the final assembly. After multiple iterations, each component was developed to be capable of completing its intended tasks. With more time together we would have assembled the prosthetic into a cylindrical

structure. The prosthetic structure would have mounting locations for each component, and a battery pack integrated with the cylinder cap. To conclude our project, we discussed recommendations for improving the functionality of the final product, and hypothesized other applications in which the implementation of these components could prove beneficial to performance or usability.

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Chapter 1: Introduction

As technology advances, the quality of life and amount of satisfaction experienced by prosthetic user increases. However, hand and wrist prosthetic devices still have significant room for improvement before they can match the functionality of the human hand and wrist. While prosthetic hands seem to be the focus of many companies, as commercial prosthetics offer multiple grips and adjustability, this often comes at the expense of wrist motion. The exclusion of two of the three degrees of freedom at the wrist can lead to compensatory movements by patients that lead to discomfort and pain over time [1, 2]. A lightweight, compact prosthetic wrist joint design with multiple degrees of freedom, paired with a capable control method, could improve patient satisfaction.

Additionally, soft robotics is a growing subsect of the field of robotics in which elasticity is introduced into actuation to achieve “soft” or compliant motion. This is desirable in prosthetic devices or other machinery with human interaction due to the similarities between soft robotic artificial muscles and human muscles. The HydroMuscle is an artificial muscle developed at WPI Popovic labs that first appeared in a conference publication in 2014, and has been a part of several graduate and senior qualifying projects in the years since. Due to its simplicity in design, efficient function, and scalability, projects involving the HydroMuscle have ranged from assistive devices to exoskeletons to stand-alone robotic devices drawing inspiration from human hands, arms, and leg muscles of humans and other mammals [3-9]. HydroMuscles were appealing for our project due to their similarities to human muscle, and for our access to Professor Popovic and other students with experience developing and implementing these actuators.

The motivation of this project was to create a HydroMuscle actuated prosthetic wrist, which would provide compliant motion in a lightweight, compact, and closed system [3, 4]. The system was designed with a biologically-inspired wrist joint with more degrees of freedom than commonly seen in commercial prosthetics. A gripper was designed to be integrated with the wrist and complete simple tasks, and code was developed to control the motors and process sensor feedback. The compact closed system was limited by length and diameter of the system below the gripper. A weight constraint was also established, although it became evident the weight was mostly dependent on the motors, and in turn, dependent on the budget. This paper will cover the research, experiments, and iterations of the aforementioned components.

Chapter 2: Background

2.1: HydroMuscles

HydroMuscles are hydraulic powered artificial muscles created in WPI Popovic labs. They have two main components: an inner elastic tubing that expands when pressurized by the fluid, and a scrunched outer sheathing that limits the radial expansion of the elastic tubing. Latex tubing is commonly used for its elasticity and its variety of available sizes, as wall thickness and length have a large impact on the performance of the muscle. Latex is also a cost effective material that offers high work cycle efficiency in the HydroMuscle design [4]. Nylon kite fabric is an accessible material for the sheathing of smaller HydroMuscles, as the thin fabric is strong enough for compact systems with lower pressure [5].

The fluid system is made up of the latex tube, the reservoir, and any transport piping in between. It is essential to ensure the system is completely bled of air once it is filled with water, as the incompressible nature of water allows for consistent position control for varying applied force. The fluid pressure within the system is dependent on the amount of tension in the latex tube [4, 7]. Actuation drives a portion of the fluid out of the reservoir and into the latex tube, forcing the tube to expand, which increases the pressure in the system. The scrunched nylon kite fabric limits the elastic tube's radial expansion, but still allows for linear expansion of the HydroMuscle. When the actuator allows fluid back into the reservoir, the fluid naturally moves as the latex tube retracts to a state of less tension. This linear motion of the HydroMuscles drives the motions of our prosthetic wrist. We chose to power our HydroMuscles hydraulically, as opposed to pneumatically, due to the benefits of the incompressible nature of water, including greater energy efficiency, control over slow motion, position control in between the two extreme positions, and less variability due to varying force on the HydroMuscle [5].

A HydroMuscle creates a linear tensile force, as does a human muscle. However, HydroMuscle force is in line with its linear expansion, while a human muscle bulges radially with contraction. The force of a HydroMuscle comes from the tensile force of the elastic tube [7]. The fluid is used to keep the latex in an extended state, and the fluid pressure reflects the force with which the latex is pulling back. This tensile force is then used to apply a pulling force onto whatever is attached to the end of the HydroMuscle. The opposing force that is applied by the attachment onto the HydroMuscle, as long as it does not surpass the tensile force of the latex tube, is reflected in a decrease in system fluid pressure.

Previous HydroMuscle Projects and Applications

The HydroMuscle has proven to have a variety of applications due to its efficiency and scalability. Previous projects prove this through the use of the HydroMuscle to closely resemble arm or leg muscles in applications ranging from assistive devices to independent robotics. HydroMuscles from one project to the next have slight differences in design and actuation, but the concept of their functionality remains constant. The main variation tends to be the dimensions of the inner latex tubing, as the wall thickness corresponds to the force output, the inner diameter relates to the volume of fluid required, and the depressurized initial length relates to the percent elongation required to achieve the final extended length of the muscle. Additionally, multiple projects used polyester outer sheathing such as UberHose, while others used nylon kite fabric. The function of the outer sheathing did not change, however [5, 9]. There has also been a comprehensive report on the capabilities of the HydroMuscle, including numerical models for the force output, strain, effective modulus, and more [4].

HydroMuscles are commonly used for linear motion, but can also be manipulated to provide nonlinear actuation, as seen in the curved muscles of the Hydro Muscle Hand Brace. In the project, careful manipulation of the sheathing was performed to control the expansion of the latex. The pressurized extended state of the HydroMuscle had curves controlled by the initial, specific folds made in the sheathing. Although these curved HydroMuscles did not produce the desired force output, the application of HydroMuscles to achieve the rotational motions involved in finger flexion and extension were very inspirational to the development of the prosthetic wrist [5].

2.2: Wrist and Prosthetics

Prosthetics are categorized by their applicable amputation level and their power source. Considering the upper body, a variety of prosthetic devices exist for amputations at the shoulder, along the upper arm, along the forearm, and more. Wrist prosthetics are suitable for a transradial amputation, or an amputation along the radius and ulna bones in the forearm. While there exist complex prosthetic hands with many capabilities and degrees of freedom, the functionality of the wrist does not seem to be as strong a point of emphasis for reasons having to do with size, weight, and control [10, 11].

In terms of power source, patients’ choices include:

- Passive – cosmetic devices without any active degrees of freedom
- Body-powered – prosthetics with motion actuated by user motion further up the arm
- Externally powered – prosthetics with motors and batteries contained in the system

And a fourth option with both body-powered and externally powered movements. Externally powered systems generally offer more capabilities than body-powered devices and are much more self-contained, as body-powered systems use straps and pulleys up the patient's arm to source power [11]. The capabilities of 3D printing also increase the appeal of externally powered systems due to the light weight of PLA.

The wrist joint is challenging to replicate as a prosthetic due to its multiple degrees of freedom, ranges of motion, size, and weight. The wrist can be rotated about three axes, although motion is coupled. Wrist flexion and extension change the angle between the palm and the anterior forearm, commonly seen in the follow-through on a basketball shot. This motion has a range from the limit of flexion to the limit of extension of about 155 degrees, with significant variance from person to person. Wrist abduction (radial deviation) and adduction (ulnar deviation) change the angle between the thumb side of the hand and the lateral forearm, commonly seen in the wrist motions of playing the drums. This motion has a range from the limit of radial deviation to the limit of ulnar deviation of about 55 degrees [12]. Pronation and supination are the rotation of the hand about the axis running through the forearm, allowing for the palm to face up or down when the forearm is parallel with the ground. Pronation and supination combine for a range of motion of about 160 degrees [13].

The wrist itself is a condyloid synovial joint composed of a complex junction of multiple carpal bones, ligaments, and tendons. A condyloid joint provides for the aforementioned flexion-extension and radial-ulnar deviation motions. Pronation-supination is actually due to rotation within the forearm, but is visually represented at the wrist [13]. The wrist joint is known as the radiocarpal joint, but hand movement is also dependent on the intercarpal (midcarpal) joint between the proximal (scaphoid, lunate, triquetrum, and pisiform) and distal (trapezium, trapezoid, capitate, and hamate) rows of carpal bones. Flexion, extension, abduction, and adduction are all achieved by movements at both the radiocarpal and intercarpal joints in differing amounts [14]. One condyloid joint would likely require significantly more structural support from tendons and ligaments to achieve the flexion-extension range of motion. With the two joints moving in conjunction, the max angle required of either joint to achieve any of the four limits is about 50 degrees [15], while the limits can be as great as 90 degrees from the neutral axis [12].

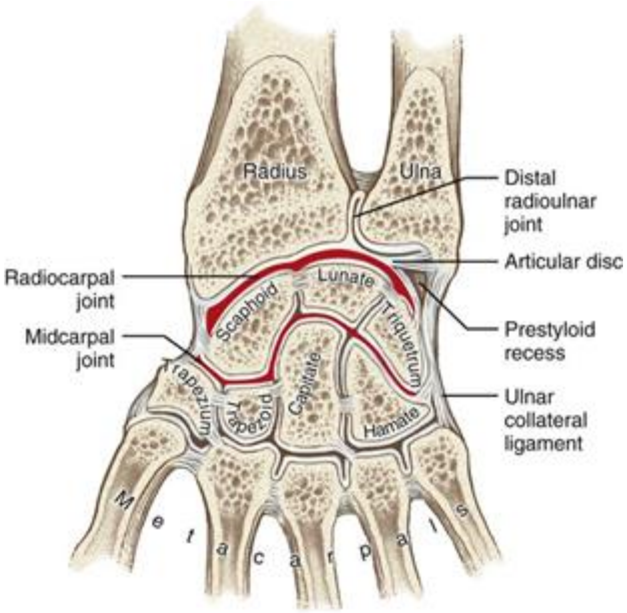

Figure 1: Radiocarpal Joint [16]

As is, the wrist already contains a complex web of ligaments linking the small bones within the two rows, the radius and ulna, and the metacarpals. The main function of the ligaments is structural support, especially for the proximal row of carpal bones [14]. Wrist motion is controlled by muscles that originate by the elbow or along the forearm. There are multiple muscles for both wrist flexion and extension, with some also being responsible for appendage flexion or extension or wrist abduction or adduction [17].

While pronation and supination are not the responsibility of the wrist joint, they are still desirable motions for transradial amputees. Often, commercial prosthetic devices will consider pronation-supination the most valuable wrist motion over flexion and deviation. These devices typically are designed so that this rotation is the one degree of freedom at the wrist, whether it is achieved passively with locking positions or actively. Prosthetic wrists are also designed as just a link between the remaining forearm and a prosthetic hand or gripper, also with the one rotational degree of freedom. Wrist designs with multiple degrees of freedom do exist, but are used for industrial robots instead of prosthetics. Prosthetic wrists are generally designed with goals of minimized volume and weight, and degrees of freedom are sacrificed to accomplish this [10].

Also, for active devices, design for several degrees of freedom significantly increases difficulty in control, which leads to the prioritization of control over the hand over multiple degrees of freedom at the wrist. A common method of control involves monitoring two muscles with opposite function. As explored earlier, the muscles responsible for finger flexion and extension originate in the forearm and are also responsible for wrist flexion and extension. Designing a device to allow both hand and wrist flexion requires a means of differentiating user intent, as the same muscles will be monitored for both actions [11]. However, the lack of degrees of freedom at the wrist can lead to discomfort and pain over time [2] as amputees must use compensatory motions to overcome these limitations when performing common tasks [1].

There also exists the potential for transradial amputees to retain natural pronation-supination through osseointegration and appropriate prosthetic design. After amputation, a patient maintains a fraction of pronation-supination capabilities linearly related to the length of the residual forearm. This natural rotation can be preserved when a prosthetic is connected to implants that are attached directly to the radius and ulna bones in a way that does not interfere with the rotation of the radius over the ulna [18]. In a 2018 study on an individual transradial amputee, it was suggested that a prosthetic designed to attach to the implants in a way that constrained their linear and angular motion but allowed for them to rotate about their axes would preserve the user’s natural forearm rotation while limiting discomfort when completing tasks [19].

2.3: HydroMuscle Actuation

Previous means of HydroMuscle Actuation

While the functional concept of the HydroMuscle is well established, the way the HydroMuscles are actuated, or the method used to control the system fluid pressure, varies between projects. One of the first major projects to utilize HydroMuscle, “Hydro Artificial Muscle Exo-Musculature” [6] published in 2014 used a hydraulic system composed of a continuously acting pump, a 5 gallon water reservoir, pressure release valve, and two solenoid valves to add and remove pressure in the HydroMuscles. Figure 2 below shows a diagram of the system.

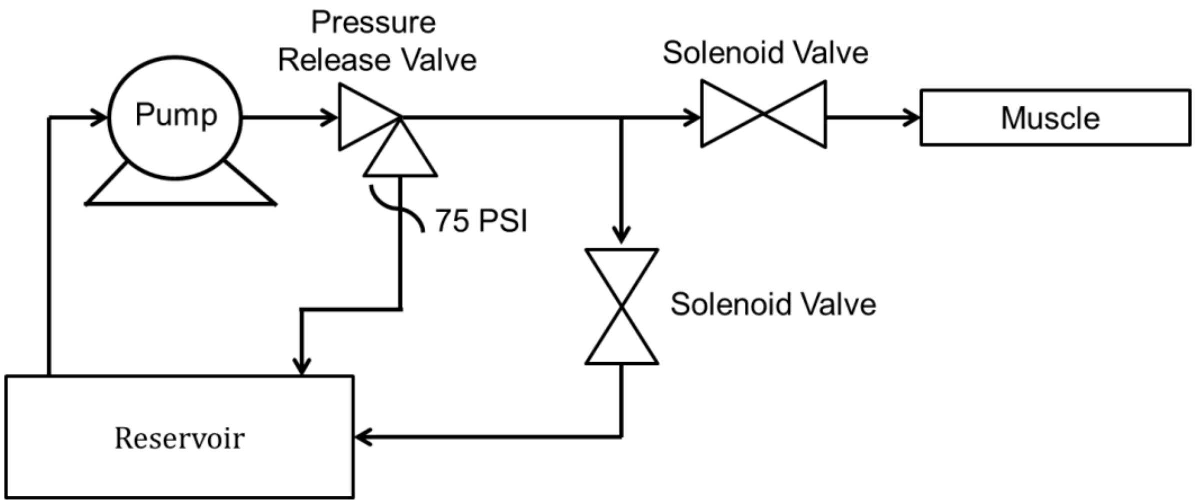

Figure 2: Hydraulic system schematic from “Hydro Artificial Muscle Exo-Musculature” [6]

From the paper, “In order to actuate the muscle, the far right solenoid valve opened for 0.3 seconds, while the discharge solenoid valve stayed closed. In that time frame, the muscle was pressurized and expanded fully. When the desired expansion is achieved, the actuating solenoid valve is closed and the fluid escapes through the pressure release valve. Essentially, this particular setup locked the muscle at any desired pressure, providing full control of the actuation. The discharge of the muscles is achieved when the discharge solenoid valve opens, allowing the fluid to return to the reservoir.” [6]. While this system worked for the scope of their project, the authors of the paper cited the size of the system as well as the many opportunities for potential leaks as one of the primary disadvantages of the design.

More recently, a 2016 project titled “Hydro-Muscle Actuated Exo-Legs for Therapy and Video Gaming” [7] utilized a system consisting of servo controlled diverter valves to regulate pressure in the HydroMuscles. These diverter valves had three states, pressurized, stable, and depressurized and were controlled by servo motors attached to physical handles on the valves. Similar to the 2014 project, this system depended on a large reservoir and a continuously running pump circulating the water throughout the system. Once again, this system worked well enough for the scope of the project, however as seen in figure 3 below, it was quite large and bulky, requiring the user to both wear a backpack and tow around a cart containing the hydraulic system.

Figure 3: Complete system from "Hydro-Muscle Actuated Exo-Legs for Therapy and Video Gaming" [7]

A 2018 project, "HydroMuscle Hand Brace" [5] featured HydroMuscles similar in size to those that we anticipated using in our design. While this project would turn out to be very helpful regarding the fabrication of small scale HydroMuscles, the hydraulic system consisted of solenoid valves paired with a large linear actuator that was connected to a 50mm plastic medical syringe, shown below in figure 4.

Figure 4: Linear actuator and syringe from “HydroMuscle Hand Brace” [5]

The linear actuator would force water in and out of the system by extending and contracting the plunger on the syringe. Although this design reduced the size and complexity of the fluid reservoir needed in the system by not having a pump continuously circulating through a closed loop, the volume of the overall system remains a limiting factor in the application of HydroMuscles. There exists room for development for HydroMuscle actuation in compact, closed systems.

2.4: Arduino Coding

The control system for this project was run by an Arduino Nano. They are very useful for the prototyping phase of a project as they can be rapidly updated with new code and have a wide variety of connection ports. For future builds of this project the Arduino Nano would be replaced by a much smaller permanent microcontroller built into a printed circuit board. These microcontrollers are often used by the hobbyist community to build digital devices with small form factors. Same as all of Arduino’s other boards, the Nano includes analog and digital input/output pins, a Mini-B USB port, an ATmega328 controller, and more. Thanks to the plethora of I/O pins the board is able to control multiple devices at once, a key feature needed for this project. The motion of the linear actuator is partially based off of inputs received from the multiple sensors used. A serial connection is also required to receive the feedback from the sensors, which is passed through the USB connection into the Arduino Integrated Development

Environment (IDE). The Arduino IDE is an open-source application structured off of the C and C++ languages. As it is open-source, anyone is able to create their own libraries and upload online for public use. Several of these libraries were used for this project as they helped to greatly decrease the amount of time needed to develop the control system.

Chapter 3: Methodology

3.1: Goal Statement

The overarching goal for our project was to design and develop a HydroMuscle-actuated prosthetic wrist. Our goal included biologically inspired wrist motion, and a gripper capable of grasping a cup. Our project necessitated an actuation system for HydroMuscle control, with programmed movements and the implementation of a force sensor feedback loop. Unfortunately, due to the COVID–19 outbreak we were unable to finish the project as a team on campus. This caused us to adjust our goals accordingly. Instead of focusing on our original goals and their corresponding functional requirements, we showed each component's final design and assembly individually.

3.2: Functional Requirements

I. Our primary goal was to have a completely enclosed system contained to the forearm of the amputee. The total weight goal was approximately 3.0 pounds, the wrist would only take 3 inches of length from the tip of the ulna bone, and the circumference of the system would be approximately 9.5 inches wide.

II. The wrist would flex and extend 155 degrees, and the radial and ulnar motion was 50 degrees.

III. The hand/gripper had one actuated degree of freedom with the ability to grasp an object with a circumference of approximately 4.7 inches wide.

IV. The system would be controlled using a sensor feedback loop to control grip force and the position of the plunger. The system would also be programmed to pick up and move objects from one location to another to prove motion capabilities.

V. Post outbreak, the goal for the team was to show each component worked on its own.

3.3: HydroMuscle

Determining HydroMuscle Dimensions

The first step for the project, once dimensional constraints were set, was to use calculations to approximate latex tubing dimensions to ensure adequate strength to actuate the wrist and fingers. HydroMuscles work due to the latex tube's desire to return to its natural state, or reduce its elongation. The important dimensions of the latex tubing are its initial and final lengths, its inner diameter, and its wall thickness. Our calculations began with finding the force generated from the latex contracting back to its rested state. To get an estimated number for the force created we used a simple calculation of using the interior pressure of the HydroMuscle and the interior area of the latex tube. This equation was then expanded to include the strain of the latex, the latex's wall area, the area the water can travel through, and latex's wall shrinkage factor. These factors also accounted for the volume of water change through the HydroMuscle and the HydroMuscle's change in linear length.

From our volumetric constraints, we decided to establish the HydroMuscle's relaxed length as 1.0" inch, and we started with initial values for the interior pressure (around 100 pounds per square inch or 700,000 Pascals) and the Young's Modulus of the latex (220 pounds per square inch or 1,500,000 Pascals). Based on the strength output measured in previous projects, we chose latex tube dimensions based on a pressurized inner radius of 3/16", and an outer radius of 1/4".

Initial Concept

Previous projects use HydroMuscles that operate on the same principles as ours, as discussed in the background. Fluid from a reservoir is driven into the latex tube, causing expansion, and a sheathing is used to force that expansion to be linear. In previous projects, the HydroMuscle is capped at one end, and the cap is fixed by a combination of glue and a clamp. The other end is attached to a linkage piece connecting the latex tube to a transport tube, through the same combination of glue and a clamp. Some of the larger HydroMuscles seen in previous projects used a special sheathing called UberHose™ in order to withstand the additional pressure seen in systems with latex tubing of greater wall thickness.

Design Iterations

We went through multiple iterations to develop our final HydroMuscle design. Our first attempt utilized nylon kite fabric sheathing, a simple plug, glue, and a clamp. From there, there were five key experiments that influenced design decisions. Our first test showed us that we needed to use a latex with a smaller wall thickness, improve our sealing, and add a support system to hold the motor in place. This led to multiple experiments with different glues and methods of clamping the tube at the ends, along with a rear support piece on the actuator. Testing also established the need for a better plug at the end of the HydroMuscle. After testing and research, a breakthrough was achieved by introducing an entire luer lock system to cap the end of the HydroMuscle. Additionally, a sheathing bag for the balloon reservoir was eventually introduced in order to prevent the reservoir from getting pinched in the gap between the plunger and the actuator wall. A final significant design development was the decision to use an animal balloon inner latex tube through the whole system instead of a separate reservoir bag, and this was inspired by continued issues of leaking at the nozzle. The inner tube is the reservoir in the

Corkscrew Actuator chamber, and is also threaded through the nozzle and latex tube, so that the only seal occurs at the Luer cap. This is an appealing solution as the balloon is not expected to undergo severe elastic deformation, as the force is still a result of the tension in the latex tube. The inner tube is stretched to match the space available in the chamber in the reservoir section, so the material will be in tension based on the dimensions of the chamber, but this is much less applied stress and change in dimensions from the relaxed state than what forces would be expected to cause cyclic loading failure of the inner tube.

3.4: Wrist Joint

The functional objectives in wrist joint design were to achieve flexion-extension and radial-ulnar deviation motions with ranges corresponding to human biology; to allow for linear actuation of these motions; and to provide a surface onto which a gripper could be implemented. Wrist design was constrained by needs to limit volume, weight, and required actuator motion.

In order to achieve a joint with two rotational degrees of freedom, two concepts were proposed. One idea was to use a combination of single axis rotations, and the other was to use a modified, constrained ball-and-socket joint. In order to ensure manufacturability, the first option was chosen, as a ball-and-socket interaction would require very smooth surface finishes and high geometric accuracy.

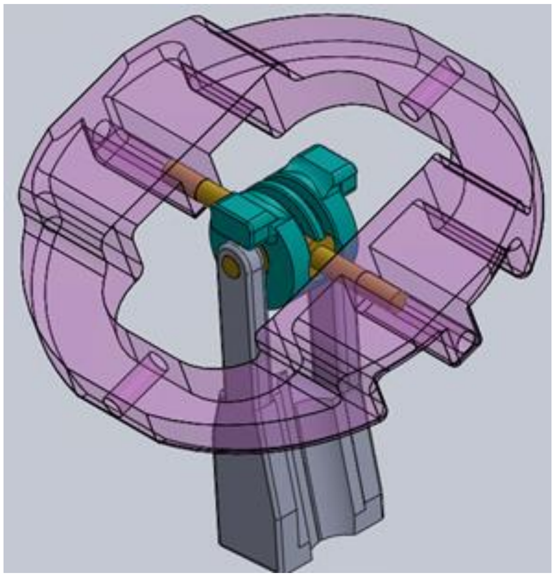

Figure 5: Wrist Joint Combination of Single Axis Rotations

The combination of single axis rotations was built on the use of a center gear linking the wrist plate to the structure. The gear has one rotational degree of freedom with respect to the structure, and the wrist plate is capable of rotation with respect to the gear. At this point, it was decided to make the gear rotation about the structure correspondent with flexion-extension motion, and the wrist plate rotation about the gear correspondent with radial-ulnar deviation.

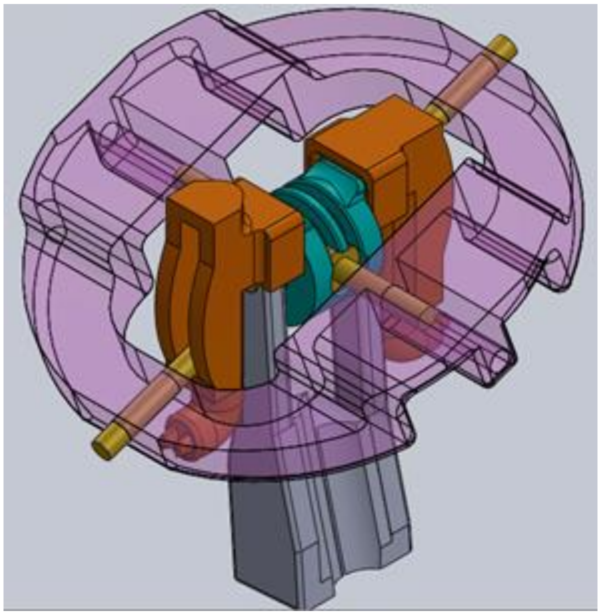

Figure 6: Wrist Joint Introduction of Arms

Arms were designed in order to prevent the wrist plate from translational motion with respect to the gear and to limit its rotation to ranges of motion matching radial-ulnar deviation. The arms attach to the gear by the gear tabs, and have slots that interact with rods attached to the wrist plate. The interaction between the slots and rods is what constrains the wrist plate. The width of the slot prevents the rods from sliding linearly, which prevents wrist plate translational motion.

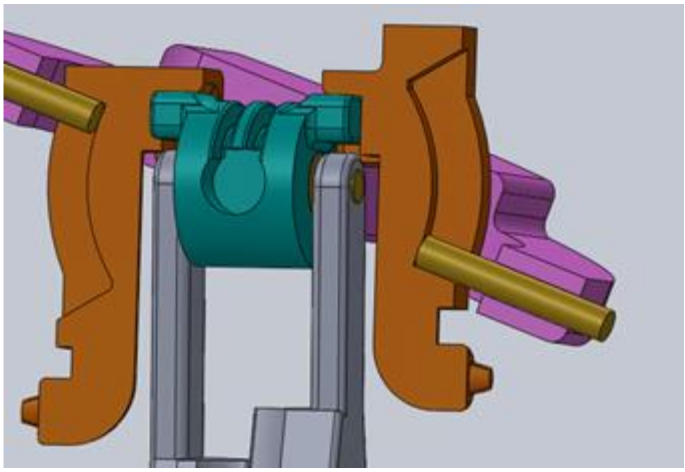

Figure 7: Wrist Joint Arm Slot Detail

The upper and lower end geometry of the slots act as hard stops to wrist plate rotation. The arms are attached to the gear in order to maintain radial-ulnar capabilities in different positions of flexion or extension.

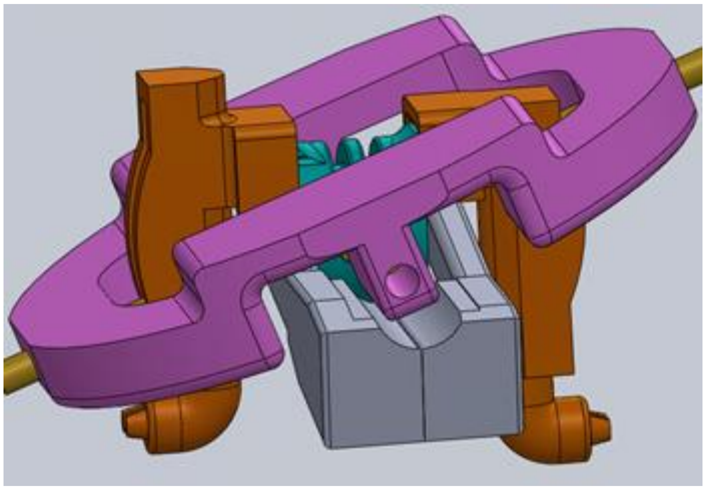

Figure 8: Wrist Joint Flexion

In order to achieve the desired ranges of flexion and extension, the wrist plate and structure required concurrent design to prevent interference. The wrist plate cutouts allow for radial-ulnar deviation to be actuated without interference at max flexion or extension. The structure was designed to have an increased cross-sectional area to reduce stress, while not interfering with the wrist plate at these extreme positions.

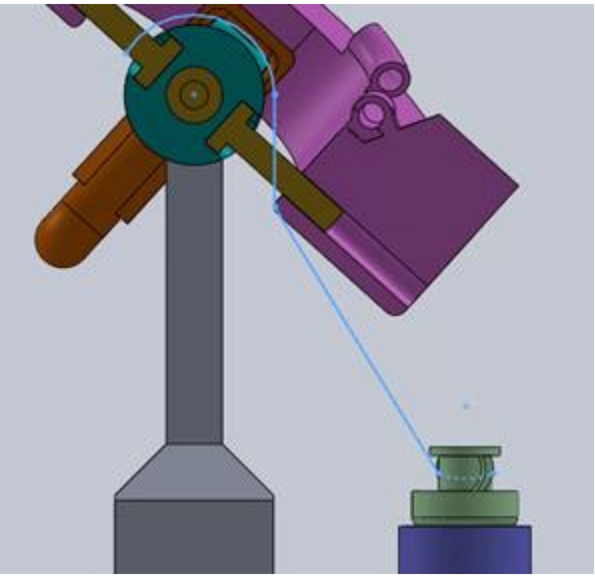

Figure 9: Wrist Joint Pulley System I

In order to actuate flexion-extension rotation with linear motion, a pulley system was planned to be used. HydroMuscle motion would drive gear rotation. As shown in previous figures, the gear was designed with ridges for the string to fit into. These ridges also reduce the effective radius of the gear in terms of the pulley system.

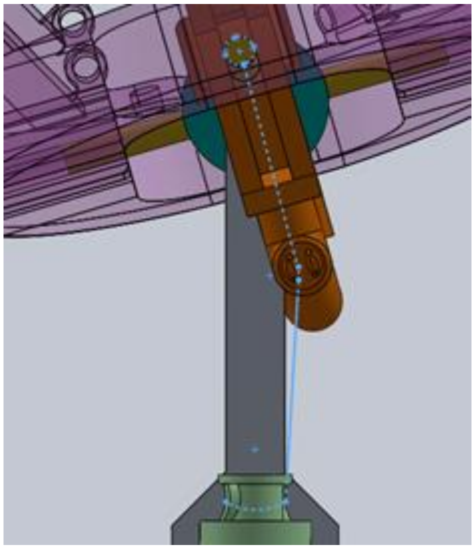

Figure 10: Wrist Joint Pulley System II

Radial-ulnar deviation was planned to be actuated with a similar pulley method, connecting the rod between the wrist plate and arm to the HydroMuscle. In order to maintain actuation capabilities at larger angles of flexion or extension, the arm was designed with a tail ridge to guide the pulley string.

3.5: Actuator

Initial Concepts

As we moved forward with the project, it was clear that we would need to design a smaller, less complicated method to actuate the HydroMuscles in our prosthetic than what was seen in previous projects. We first started thinking of ways that we could utilize a standard medical syringe similar to the one mentioned in the hand brace project above because we were fond of the simplicity it provided. The first thing we looked into was whether or not it would be feasible to simply just miniaturize the system used in the hand brace, essentially looking to see whether or not a small linear actuator paired with a medical syringe would function well and also fit into our size constraints. After researching the needed components, there were two major issues with using this type of system. First, there were very few linear actuators on the market that are small enough and powerful enough to handle the pressures we were planning on utilizing. Second, after some discussion, we realized that the force outputs required to move the plunger in a syringe are not linear, as high force is needed to overcome the initial friction between the seal on the plunger, but once the plunger is moving it does not require as much force from the actuator. This phenomenon is due to the fact that the critical seal in a syringe is due to friction between the plunger itself and the inner surface of the syringe body. Because of these reasons, we decided that utilizing a syringe would not be ideal for our prosthetic.

After identifying the unique sealing characteristics of a syringe and the force requirements they required, we then decided to pursue an actuator design that would work around this issue by instead relying on a small plastic bag to act as the reservoir for the system. By connecting the HydroMuscles directly to the flexible reservoir bag, we realized that we would be able to reduce the complexity of sealing between the plunger of a syringe and the inner surface of the syringe housing. Building on this idea, we realized that by choosing a flexible, elastic material for the reservoir bag, when we filled the system with water the reservoir would be able to fill the space of the enclosure shape. Because of this, there would be no seal between the reservoir and inner surface of the space it filled, meaning we would be able to push on the bag with a plunger without having to work around the issues mentioned above. With these ideas in mind, the first concept for our actuator was born as essentially a flexible reservoir bag enclosed in a syringe.

However, from our previous research, we knew that there were very few linear actuators on the market that were small enough to be utilized to move the plunger in the system and push on the enclosed reservoir. To work around this, we came up with the idea of using a rotational motor to spin a threaded shaft on which a nut would be restricted from rotating. With the rotation of the nut constrained, the only way for it to move would be linearly along the length of the threaded shaft. The general concept for using rotational motion to drive linear movement can be seen in the figure below. This concept of using a rotational motor to push a plunger against a sealed, flexible reservoir of fluid in order to force water into HydroMuscles became known as the Corkscrew Actuator within the project.

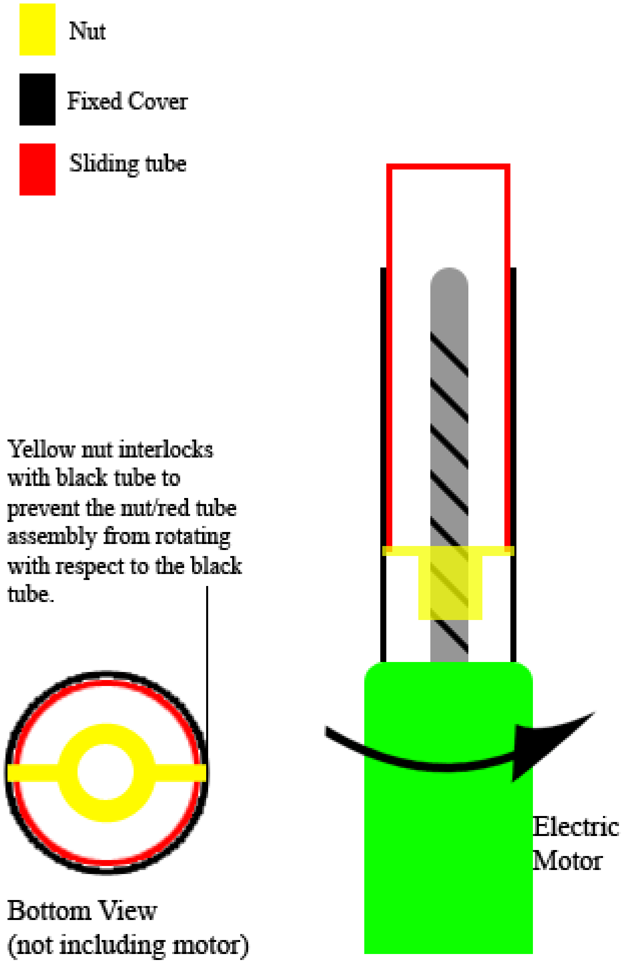

Figure 11: Rotation based traveling nut linear actuator [20]

It is desirable to utilize the Corkscrew Actuator and HydroMuscle instead of rigid components and elastic tendons due to the potential implementation of valves to allow for the actuation of multiple HydroMuscles from one actuator. The use of an elastic tendon would require a motor for every degree of freedom. The design for more degrees of freedom and the implementation of valves was beyond the scope of this project, but could be used to further develop the design in the future, potentially leading to more fingers with more degrees of freedom at the hand, still driven by one corkscrew actuator.

Corkscrew Actuator Iterations

The Corkscrew Actuator was one of the most critical components of this project, and as a result the design went through many changes throughout the course of the academic year. The very first rough CAD model of the Corkscrew Actuator can be seen below in Figure 12.

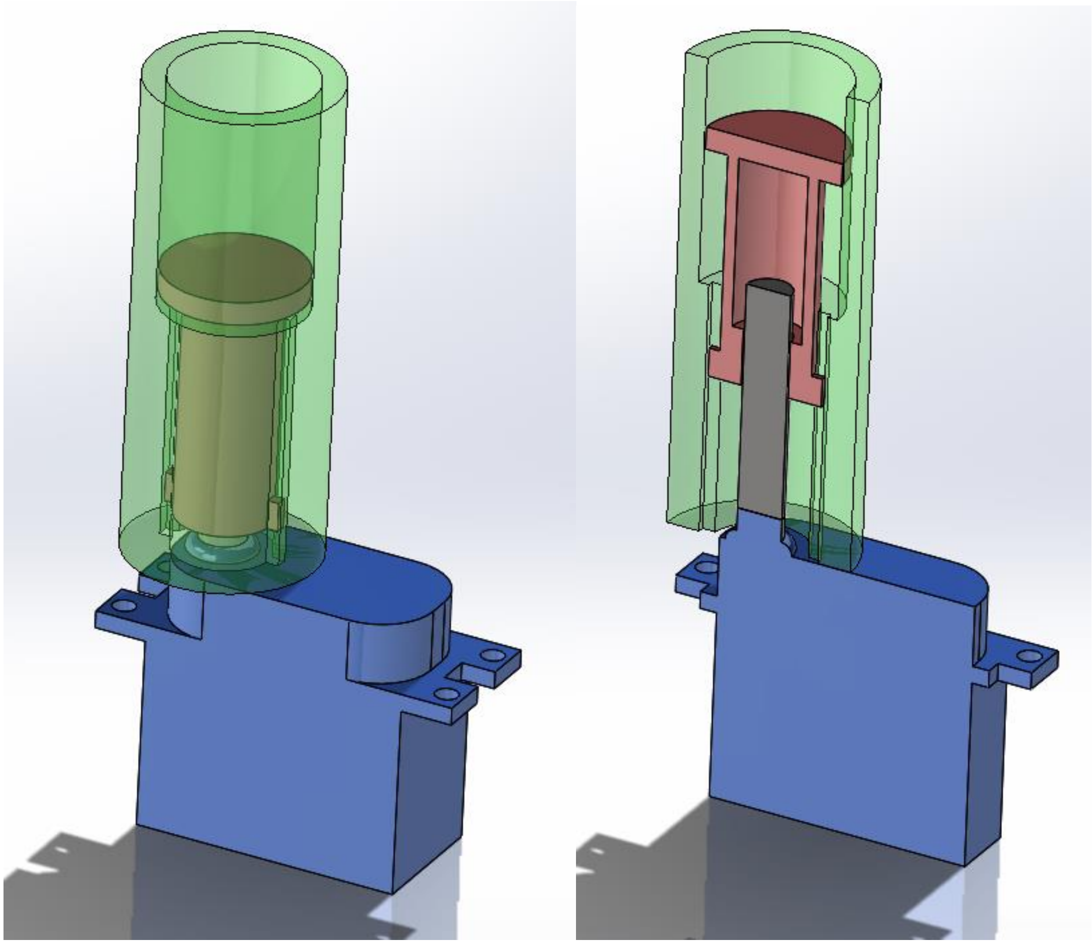

Figure 12: Initial Corkscrew Actuator CAD model

This model was very primitive, using a generic motor model as well as ballpark estimates on the overall size, however it allowed us to visualize some important aspects of the concept. Two thin slots running vertically through the length of the cylinder restricted the plunger from rotating via two tabs on the body of the plunger itself. One important realization from this model was that we would have to design the plunger itself with a hollow body to make room for the rotating motor shaft as the plunger traveled along the length of the cylinder. Additionally, this model helped us start to think of the way that we would manufacture the actuator itself. Due to the ability we had to quickly create new parts through the 3D printing lab on campus, we as a group decided that 3D printing these components would be our best bet, and as a result we decided to optimize our future design for the printers by designing features with manufacture and printability in mind.

The next iteration of the Corkscrew Actuator built on this principle of designing the components for easy 3D printing by reworking the feature that would restrict the plunger from rotating. Additionally, this iteration featured a reservoir with a volume equal to the volume of fluid that we initially calculated would need to be forced into the HydroMuscle. With this second iteration, we also realized that the motor that we had initially decided to use did not have a threaded shaft, so this model featured the first design of a 3D printable coupler that would connect the shaft from the motor to a seperate threaded shaft. Figure 13 below shows this iteration, highlighting the new triangular slot to restrict the plunger from rotating.

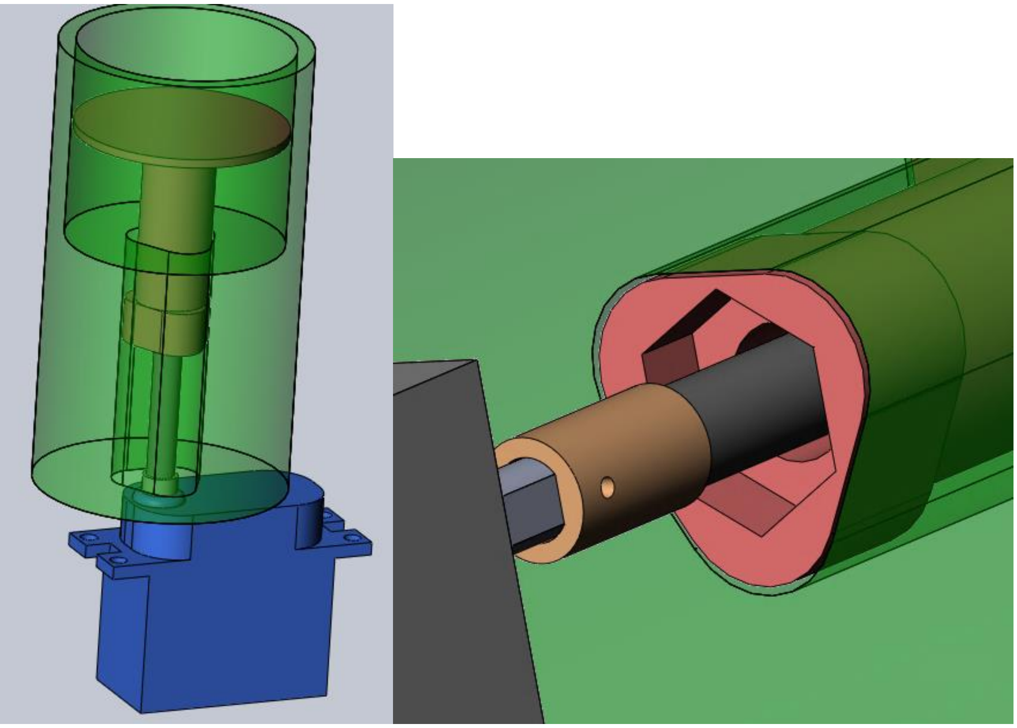

Figure 13: Second iteration of Corkscrew Actuator featuring the rounded triangular slot that would remain present for all future designs

Shortly after this iteration, we settled on the first motor that we wanted to test the actuator with, the Greartisan DC 12V 600RPM N20 High Torque Speed Reduction Motor. Therefore, the next version of the actuator was the first to be realistically sized to work well with a real motor. This iteration was also the first to feature a top cap that would cover up the reservoir chamber and force the water into the HydroMuscle. At this point in the project we hadn't finalized a nozzle design connecting the latex HydroMuscle directly to the actuator, and were planning to utilize a hollow pen cap that we would glue to both the top cap and the latex itself. Figure 14 below shows the CAD with both the cap on and hidden to show the reservoir chamber. It is also important to note that at this phase in project development, we were planning on using a latex finger cot as the fluid reservoir, and for this design expected to secure the finger cot into the chamber by both gluing it to the plunger and pinching it in place between the cap and cylinder body.

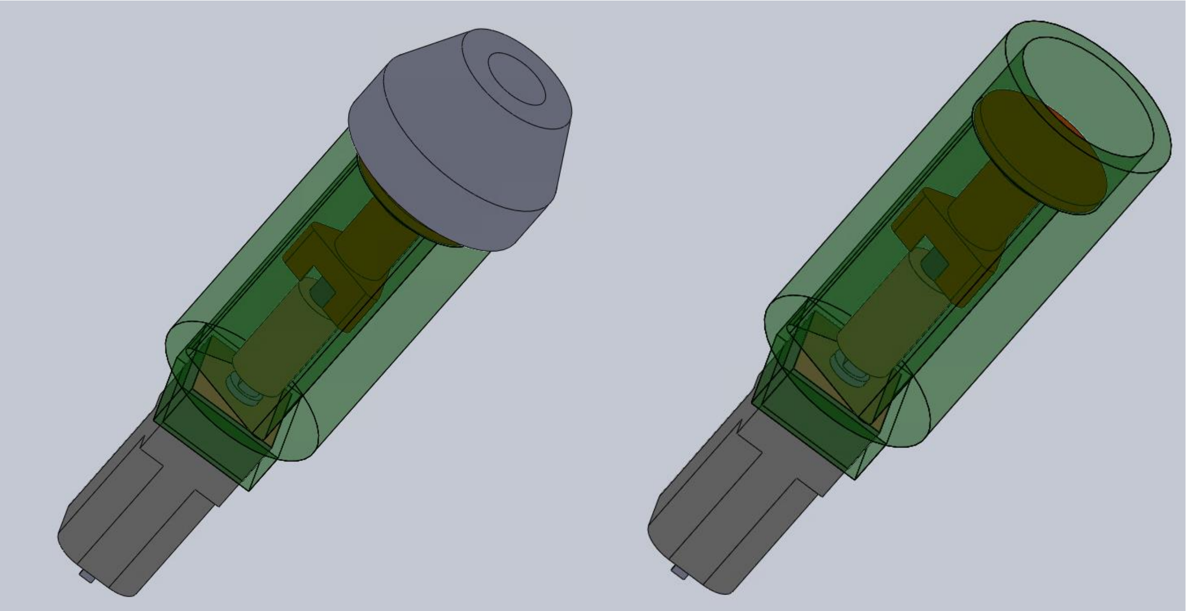

Figure 14: Third iteration of Corkscrew Actuator featuring realistic sizing for first motor choice and chamber top cap

With this version of the Actuator CAD finished up, we were able to 3D print the first physical prototype of the Corkscrew Actuator to test with the chosen motor. The plunger piece was 3D printed with the same diameter as the reservoir chamber and then sanded down by hand to ensure the best fit within the chamber. To actually test however, we had to also print and assemble the tiny coupler to connect the threaded shaft to the motor. This coupler would prove to be one of the most finicky components throughout the whole project as the diameters and overall size of the print were very small. We had settled on using 5-40 threaded shaft and nuts due to them being small enough to fit into the actuator, but not too small that we would have to spin the motor too many times to achieve the needed linear travel. Additionally, we needed to glue the nut into the actuator plunger. Figure 15 below shows the threaded shaft fixed onto the motor and figure 16 shows the nut fixed into the bottom of the plunger. Details from this test can be found in experiment 1 in the testing section.

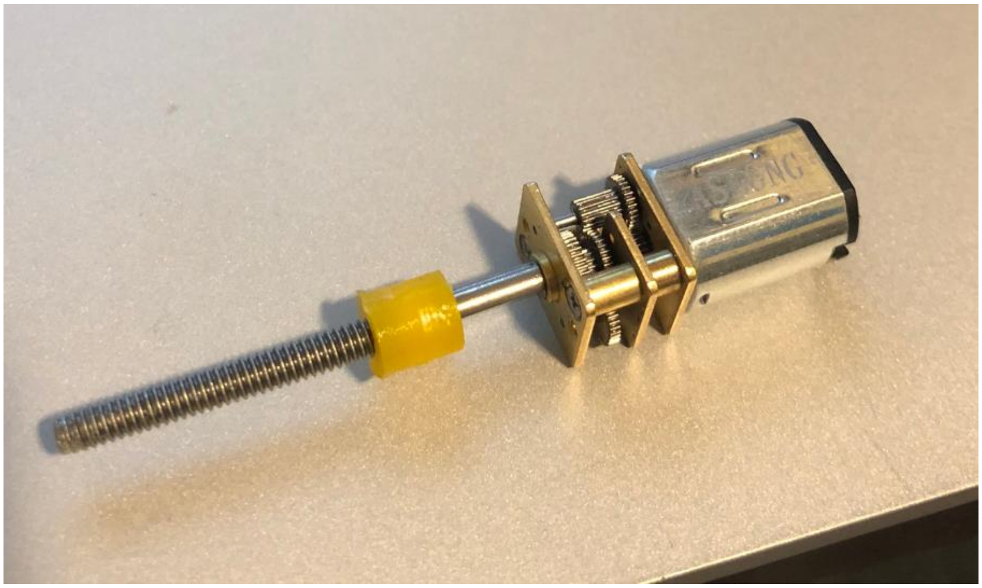

Figure 15: 3-D printed motor coupler

Figure 16: Nut glued into bottom of actuator plunger. Note the sanded edge of the circular portion

From these first tests with the Corkscrew Actuator, we were able to identify a few key takeaways. First, the concept of using the motor to drive linear motion worked well in the real world and not just theoretically as the punger visibly traveled up and down in the reservoir chamber. Second, we realized that we would need a way to secure the motor in place on the bottom of the actuator, as the force applied to the plunger caused the motor to be pushed out of its fitting. Due to the motor not staying put under force, this initial test did not prove if the motor was sufficiently strong enough to actuate the HydroMuscle. Third, we decided that we would need to design a nozzle to connect the HydroMuscle to the system. Finally, we were not happy with securing the latex finger cot in place by pinching it between the top cap and cylinder body due to leakage.

Building on these key takeaways, the next major iteration of the Corkscrew Actuator featured a piece that would lock the motor in place, as well as a nozzle piece to both better secure the latex finger cot in the reservoir chamber, and connect the HydroMuscle directly to the actuator. Small bolts and nuts would be used to fix all of the separate parts together, and this method of securing the parts would remain constant throughout all following iterations. Figure 17 shows the updated design with the most notable changes.

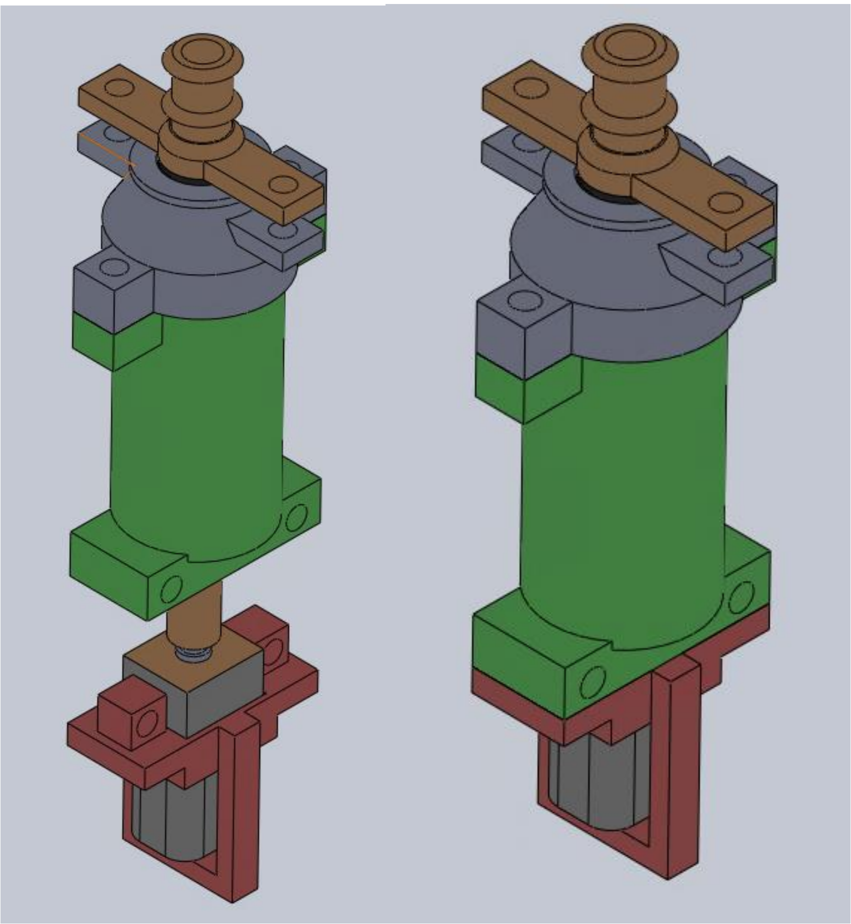

Figure 17: Fourth iteration of Corkscrew Actuator. Updated nozzle in orange and motor fixing piece in red

The top cap and nozzle of this iteration of the actuator were updated in an attempt to create a better seal between the reservoir and HydroMuscle. The extended upper geometry of the nozzle and the ridges provide material for the latex tube to slide over and be glued to. In assembly, the latex finger cot was inserted through the hole in the top cap and a small O-ring was placed on top of the hole before the nozzle was secured in place. Any excess material of the finger cot could then be stretched over the circular lip on top of the cap to fix it in place. Figure

18 below shows a detailed modeled view of this system, and Figure 19 shows the real world prototype.

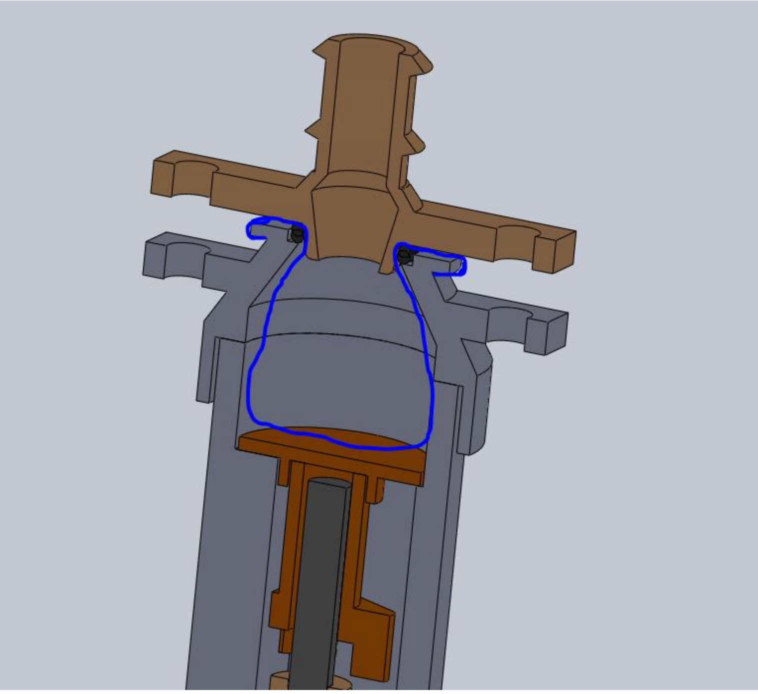

Figure 18: Updated nozzle concept. Blue line represents the latex finger cot and how it is secured between the O-ring and orange nozzle

Figure 19: Prototype of O-ring nozzle concept used for testing

After printing these parts and testing this version of the actuator, it was clear that the O-ring sealing concept was completely ineffective. The contact between the O-ring and the surface of the latex finger cot failed to actually seal the water in the system, and as such we were once again unable to test if the motor was actually capable of extending the HydroMuscle. Furthermore, we decided that we needed to redesign the volume of the actuator to allow for more water in the system while at the same time removing the space created by the tapered actuator cap as we believed that the fluid in the reservoir would expand into this excess space instead of into the HydroMuscle. Details from this test can be found in experiment 2 in the testing section.

To address this need for a working seal between the reservoir and the HydroMuscle, we decided to try incorporating the latex finger cot into the seal between the HydroMuscle and the actuator itself. To do this, we redesigned the nozzle and top cap pieces, combining them into one piece that would serve to cover the actuator cylinder and also connect the HydroMuscle to the system. The excess space in the cap was also removed by flattening out the surface where the reservoir would press up against when under pressure. Additionally, we increased the volume of the system by expanding the diameter of the reservoir chamber. Figure 20 shows this updated nozzle/top cap design.

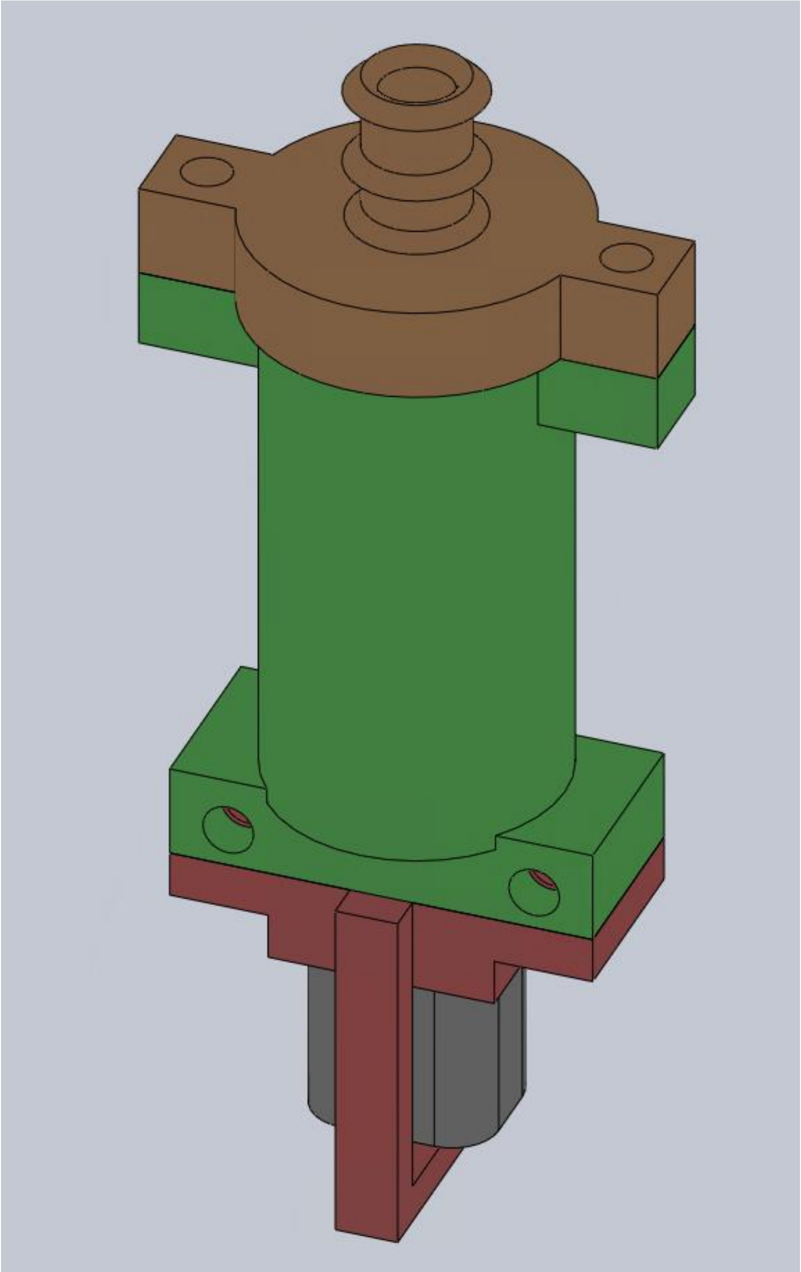

Figure 20: Fifth iteration of Corkscrew Actuator with motor brace

In assembly, the latex finger cot would be inserted down into the chamber via the hole in the nozzle, and then the excess finger cot would be stretched up and over the nozzle. The HydroMuscle would then be stretched onto the nozzle, over the latex finger cot and secured in place with the string and a layer of superglue along the base of the nozzle. Figure 21 shows this sealing system in detail.

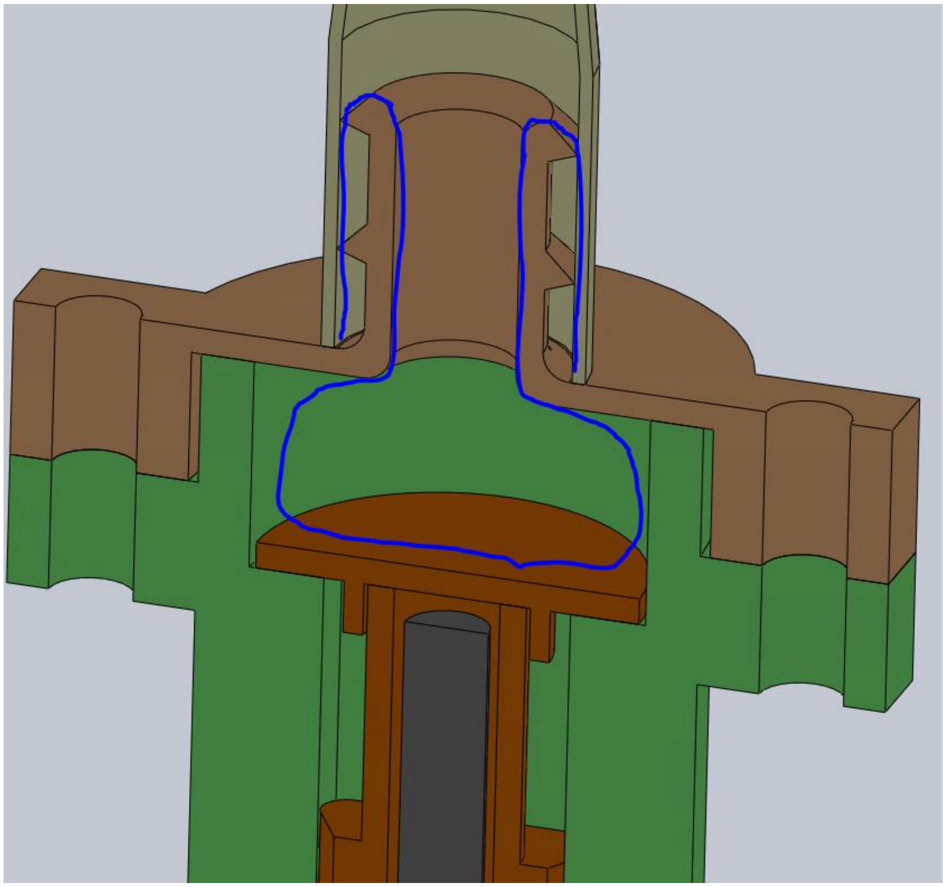

Figure 21: Updated nozzle sealing system. The blue line represents the latex finger cot being pinched between the nozzle and the HydroMuscle

Once we had printed the updated actuator parts, connected the finger cot and HydroMuscle to the nozzle and waited for the glue to dry, we were able to test if the updated actuator design resulted in HydroMuscle extension when pressing on the plunger by hand. A description of this test can be found in experiment four in the testing section. While the updated sealing method worked well enough, this test showed us that we needed to redesign the actuator to contain an even larger volume of liquid as well as incorporate a way to prevent the reservoir from being pinched between the plunger and actuator cylinder.

The next major iteration of the actuator design acted on the takeaways from the previous test by increasing the volume of the reservoir chamber and adding a lip to the bottom of the actuator top cap. This lip would allow for a protective sheath of kite fabric to be tied around the latex finger cot reservoir to prevent the latex from being pinched, as noted in the HydroMuscle section. Figure 22 shows this updated chamber and nozzle design, and Figure 23 shows the protective sheathing around the finger cot reservoir.

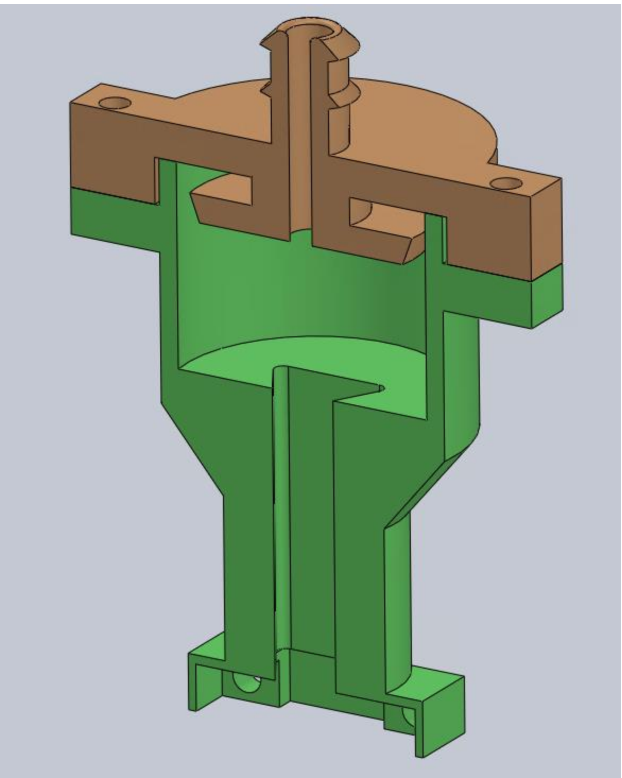

Figure 22: Updated actuator and nozzle components featuring larger volume and lip for attaching protective sheathing

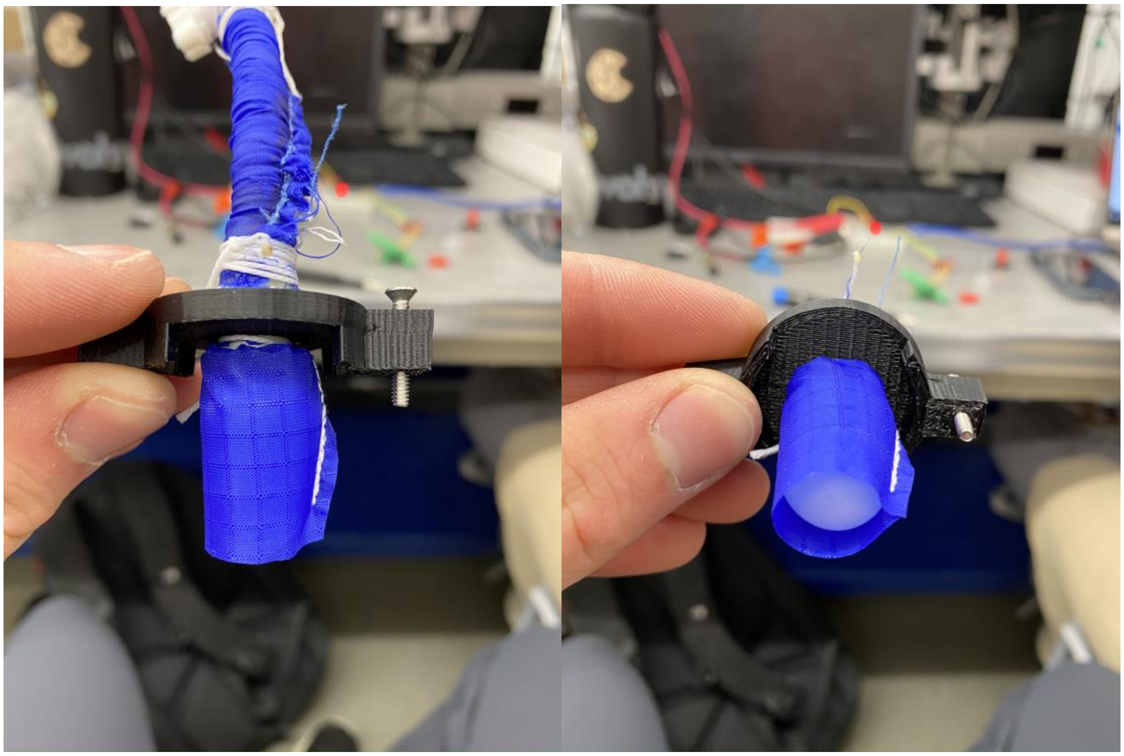

Figure 23: Protective sheathing secured to the nozzle and surrounding the latex finger cot

With the new iteration of the actuator printed, we were able to manually test the actuator by pushing on the cylinder to see if A) the added sheathing would prevent the reservoir from rupturing, and B) if the increased volume would result in HydroMuscle actuation. After this manual test resulted in successful HydroMuscle actuation with no leaks or sealing issues, we decided that we were finally able to test if the original motor would be strong enough to extend the muscle. Unfortunately, as soon as the motor was secured in place and turned on, it was clear that there was not sufficient strength as the motor instantly stalled out. We decided to begin searching for an alternate motor candidate as well as experiment with changing the shape of the reservoir chamber to see if it would be possible to reduce the needed force.

After the motor was not able to extend the HydroMuscle, we started thinking of how the geometry of the chamber itself contributed to the force that the motor would need to output. As the resulting force on a surface is equal to pressure multiplied by the surface area, we realized that if pressure in the system was constant, we would be able to reduce the force present on the plunger by reducing its area and therefore reducing the diameter of the chamber. However, in order to keep the chamber volume the same, this would mean that we would have to increase the length of the chamber to compensate for the smaller diameter. To test if reducing the diameter of the reservoir chamber actually resulted in a lower required force, an updated version of the actuator was designed that featured a smaller diameter but longer chamber length. Figure 24 below shows the two different chamber configurations next to each other.

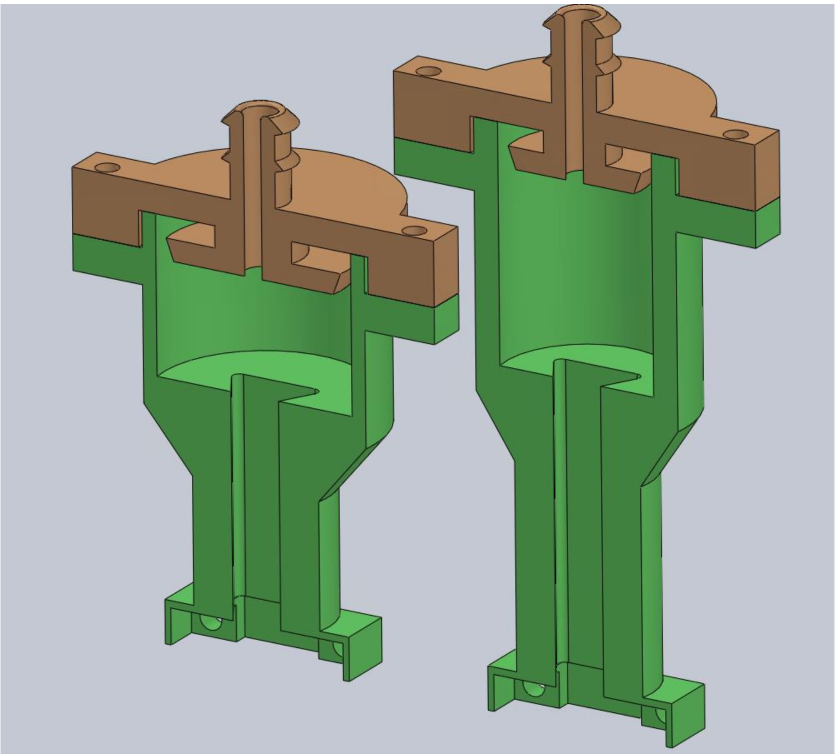

Figure 24: Original chamber design (wide diameter, short length) and new chamber design (skinny diameter, long length)

With both of the actuator configurations printed, we were able to glue the HydroMuscles to the nozzles and compare the force needed to extend the muscle for each design. As we had hypothesized, the skinny, long chamber volume was significantly easier to manually actuate than the original wide and short volume. While we understood that this would mean the motor would have to rotate more times to completely extend the muscle, we decided to move forward with the smaller diameter chamber as the main actuator configuration.

This led to the final state of the Corkscrew Actuator. The lip on the bottom of the nozzle was given an angle in an attempt to reduce the pressure associated with moving the fluid through the small diameter of the nozzle. Instead of the latex finger cot, the final version of the fluid reservoir is made from a long animal balloon running all the way through the length of the HydroMuscle latex and down through the nozzle into the chamber. This allowed for a larger nozzle inner diameter due to the fact that a water-tight seal between the latex tube and the nozzle outer geometry was no longer needed. The edge of the plunger was also curved to better conform to the bottom of the reservoir. Figure 25 shows this animal balloon reservoir system in detail.

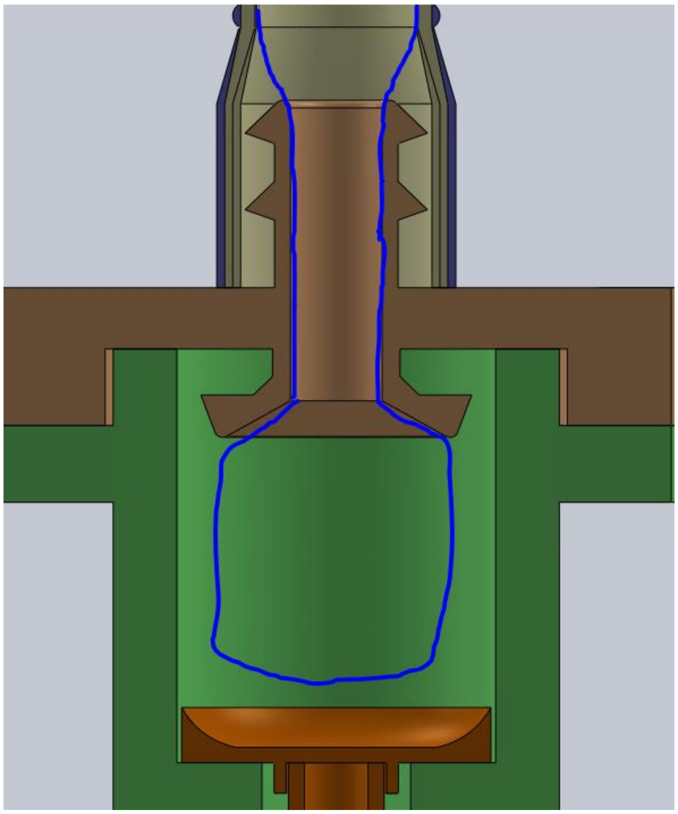

Figure 25: Final reservoir featuring an animal balloon running through the entire system to reduce leaks

Additionally, the final iteration of the Corkscrew Actuator features a motor housing and fixing method redesigned to work with the final motor chosen for the project. The new motor is circular as opposed to the rectangular shape of the original motor, and features mounting holes on its top face which will be used to secure it to the actuator via two simple bolts on the actuator cylinder.

3.6: Motor

Finding a motor that worked well for this project posed many different challenges that needed to be taken in accord. The ideal motor for the design would have a high torque, high rotational speed, small dimensions, low weight, and low price. An initial goal was to have the capability to pick up an object of about 1.5lbs while also having a reasonable speed of 45rad/s. Size was an essential consideration as the three motor system needed to be able to fit within the dimensions of a human wrist. This ended up being much more difficult to achieve than initially thought, mainly due to budget constraints. Most motors that are small are not particularly powerful, there was a balance that needed to be found to try and stay as close as possible to our goals. Another issue that we ran into later in the project was shipping times. As

COVID-19 began to shut down factories and shipping from China the time to receive these parts would take over a month. This cut down our available options even further as we needed to try and test the system as soon as possible.

Figure 26: Greartisan DC 12V 600RPM N20 High Torque Speed Reduction Motor

The first motor that we chose, pictured above was a Greartisan DC 12V 600RPM N20 High Torque Speed Reduction Motor. It was perfect for our size and speed constraints, but upon further testing was not powerful enough. The motor would usually reach the stall torque as soon as it would be turned on, not rotating the Corkscrew Actuator at all. Obviously this was not desirable for a working project, so we went back to our goals to see what could be changed to fit a more powerful motor. After consulting with Professor Popovic, we decided that the DFROBOT FIT0521 would be a much better fit. While it is only 210 RPM as opposed to the 600 of the previous motor, the stall torque of the new motor was a little over 3 times larger at 980 mNm.

Figure 27: DFROBOT FIT0521

Another advantage of the FIT0521 is that it comes with a hall effect sensor built in. From the initial planning of the project, we wanted to add one into the motor system somehow. Having the motor manufactured with it built in greatly simplified a lot of the programming that was needed for the connection to work properly.

3.7: Gripper

The main functional goal of the gripper was to be able to grasp a cup. In order to achieve this, a finger with two bodies and wrist plate extensions for mounting were designed. Gripping, or the simultaneous contraction of each finger, was planned to be actuated by HydroMuscles at the fingers linked back to one Corkscrew Actuator below the wrist. This plan created two main goals for finger design: simultaneous smooth rotation of both finger bodies; and rotation driven by linear actuation. While a curved HydroMuscle could have been designed into the finger, reaching into both bodies, linear HydroMuscle motion generates the most force.

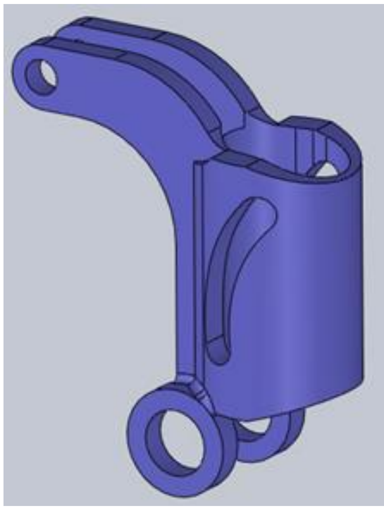

Figure 28: Gripper Finger Lower Body

The finger lower body was designed with points for connection to the wrist plate and to the finger upper body, curved slot geometry for actuator interaction, and a hollow interior to house the HydroMuscle. The curved slot geometry allows for a smooth change in angle as the HydroMuscle contracts linearly. A rod from the top of the HydroMuscle reaches to the slots.

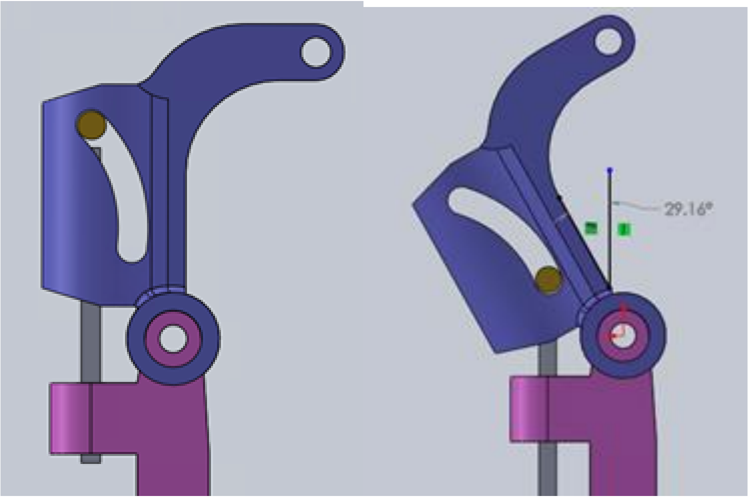

Figure 29: Gripper Finger Lower Body Extension and Flexion

Both bodies were designed for a range of motion of at least about 30 degrees and at most about 45 degrees with respect to their axes of rotation.

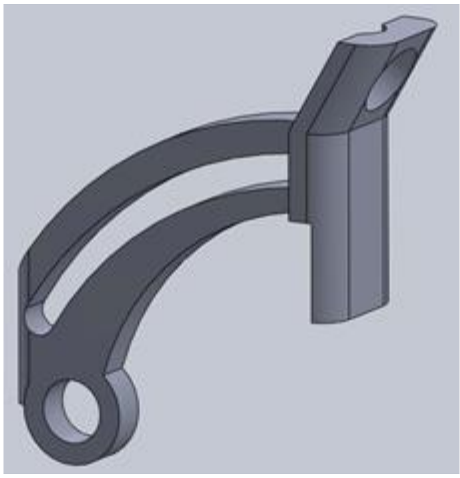

Figure 30: Gripper Finger Upper Body

The finger upper body is a slim design, as it does not need to house the HydroMuscle. It also has a curved slot to interact with a rod. The fingertip was designed to maximize contact area with an object in the gripper closed configuration without interfering with the finger lower body. Smooth rotation of the finger upper body required an axis of rotation further back than that of the lower body, which explains the handle upper geometry of the finger lower body.

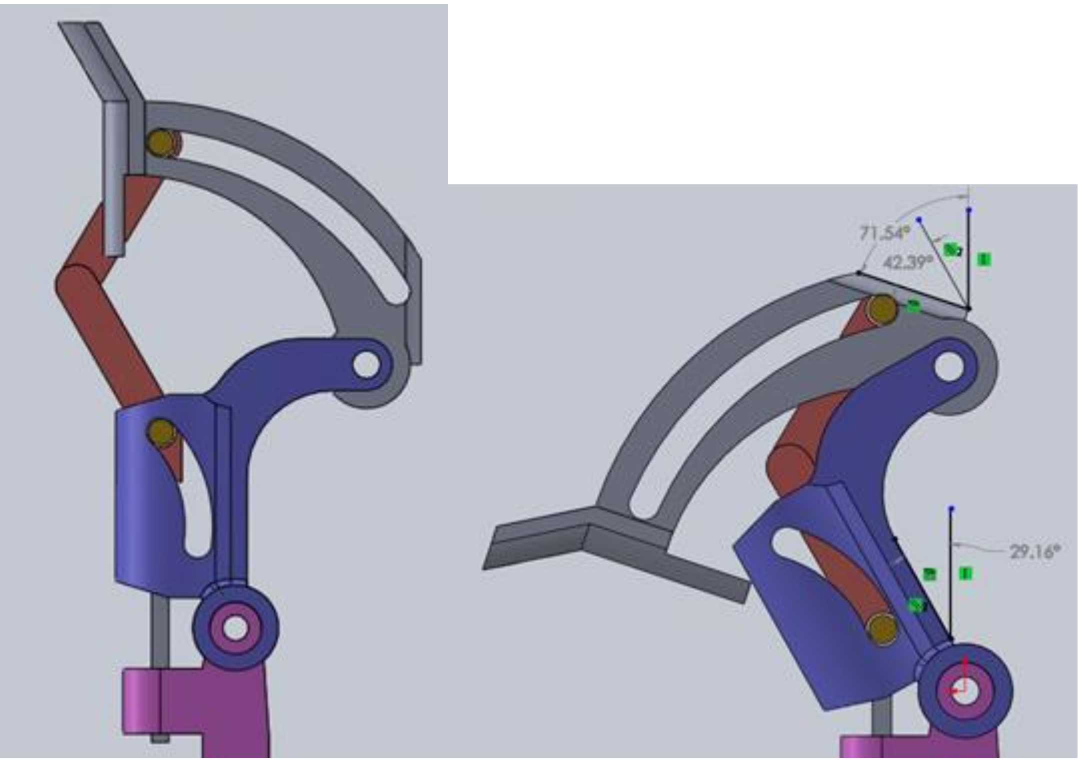

Figure 31: Gripper Finger Extension and Flexion

The curved slots of both bodies were the most challenging features to design out of the gripper assembly, as an iterative approach was taken in the 3D modeling of the parts. The slots could not force the parts to be too big, or extend in a manner that would interfere with the capability to grip. Also, it was required that linear actuation at a constant speed would not result in finger body motion of widely varying speed. There likely is room for improvement in the design of the curved slots and the finger bodies as a whole, but the printed parts, once assembled, achieve the desired function.

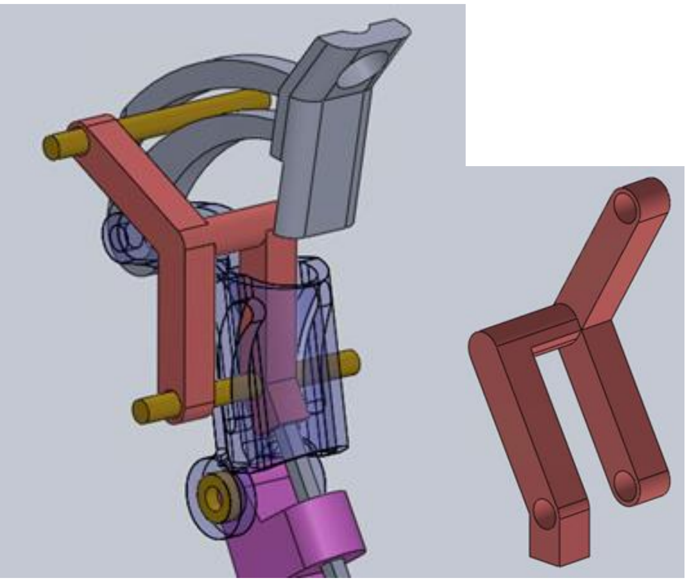

Figure 32: Gripper Finger Linkage Piece

In order to simultaneously drive the rotation of both finger bodies, a linkage piece was necessary to transfer the motion of the HydroMuscle to the finger upper body. The main challenge of the design of the linkage piece was to integrate it into the system without necessitating any changes to either of the finger bodies. The linkage piece is angled in order to avoid interference with the finger lower body, and the upper geometry is angled in order to maintain verticality between the two rods it connects to.

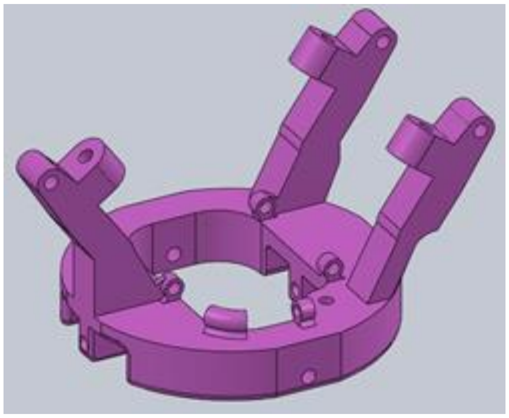

Figure 33: Modified Wrist Plate

The wrist plate was modified to have three extensions for mounting of the finger subassemblies. The angle of the extensions was iterated to create a closed configuration with a circular grip. As the angle of the extensions was changed, the lower geometry of the extensions was adjusted to maximize support to the base of the plate without extending over the plate lip. The tabs off the extensions were designed to hold the HydroMuscle, and maintain the linearity of the motion.

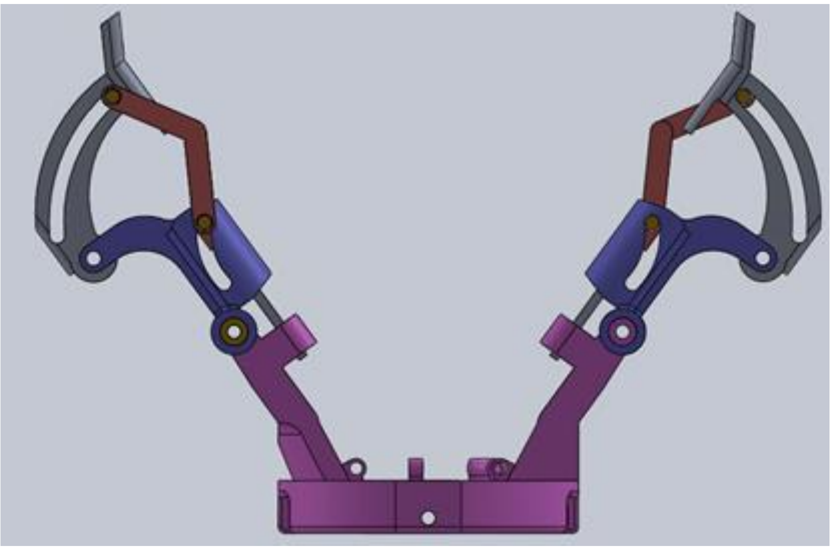

Figure 34: Gripper Extension

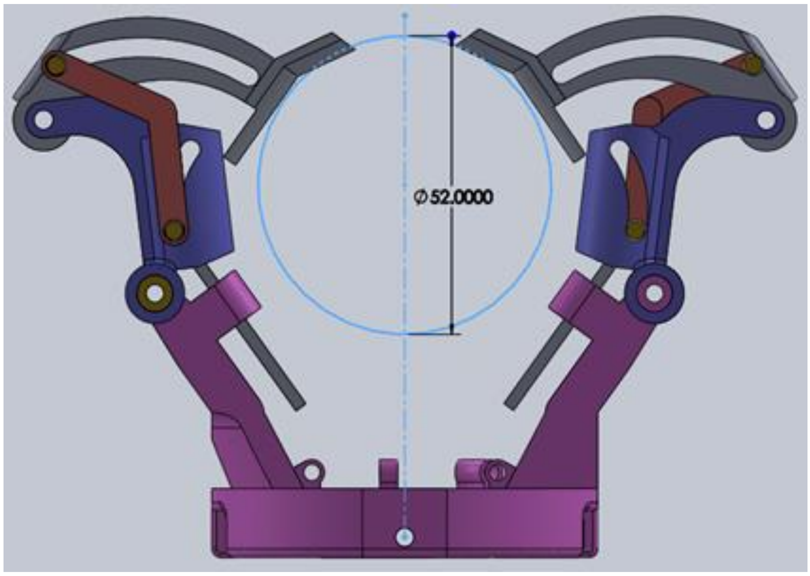

Figure 35: Gripper Flexion

Sheathing or fabric was planned to be used to cover the base of the wrist plate and close the grip, lining up with the grip circle shown in the figure, which also indicates a grip diameter of approximately 52mm.

3.8: Code

To get the code working as planned, with a feedback loop from the sensors as well as fine motor control, it took multiple tries to organize and ensure compatibility. In the beginning stages of the project, we met to discuss how everything was going to work and what was needed to complete the tasks. We decided that with the three motors the best way to control them would be with an Arduino Nano and two DC motor controllers, as each one can send and receive signals from up to two motors. The feedback loop was created using data pulled from the hall effect sensor on the motor and the force sensor on the fingertip of the hand. Further updates to the system over the course of the project included the addition of a Proportional, Integral, Derivative (PID) system. This system continuously calculates an error value as the difference between an endpoint and the current location. This value is then applied to a correction based on the namesake PID. For our project it was used to ensure as little overshoot and correction as possible in the rotation of the motor. Any extra grip or not enough grip could cause complete failure in the system, something that we did not want to run into. While our system could not be properly calibrated as the entire prosthetic was never assembled, it was a good start that could be easily fixed if it were finished.

3.9: Final Designs

3.9.1: HydroMuscle

The final HydroMuscle design used in our project consisted of a latex tube with an inner diameter of 5/16” and an outer diameter of 1/4”, a sheathing and bag of nylon kite fabric, an inner tube of thinner latex, and a Luer cap. The final design excluding the actuator volume was approximately 3.75” long before extension. The sheathing is made to be at least twice as long as the latex tube so that it can be sufficiently scrunched and not limit latex expansion.

The latex tube provides the strength of the system, but with a greater wall thickness comes greater pressure in the system. Greater pressure increases the risks of inner tube rupture and leaking at the cap, along with necessitating a more powerful motor. Our design goal was to lift a light object, so overall volume was prioritized over strength. Motors do exist that are both compact and very strong, but they are beyond the budget of this project, and would invalidate the concept of a cost-efficient design.

The sheathing is very similar to that seen in previous HydroMuscles, but the bag, made of the same material, is a new development. The bag protects the reservoir, or the bottom of the inner tube, from the gap between the plunger and the Corkscrew Actuator body. Without this bag, there is a much greater chance that the inner tube could get caught in the gap, which could lead to tearing, and system failure. The bag is tied off around a lip on the nozzle part, and has a diameter less than the diameter of the plunger, to prevent the inner tube from radially expanding to a size that could get caught in the gap.

The inner tube of thinner latex was an important development to the project in order to reduce the number of seal points from two to one, and to allow for a smoother transition from reservoir to latex tube. With the inner tube, the only seal point is at the luer cap, as opposed to previous iterations requiring an additional water-proof transition from reservoir bag to latex tube.

Figure 36: Inner Tube inside of the Latex Tube

The Luer cap was another important development to the design of the HydroMuscle, as it allowed for a volume-efficient means of filling and bleeding the system. The Luer cap is sealed until a syringe is twisted into it, so that flow through the cap in either direction is only allowed when a syringe is attached. This saved a significant amount of space compared to a more common lever valve, and provided a much easier filling process compared to attempting to remove a larger valve and plug the system without reintroducing air or losing fluid.

The final HydroMuscle assembly process is as follows:

A) Supplies
   i. Super-Soft Latex Rubber Tubing for Air & Water 1/4" ID, 5/16" OD
   ii. 1/4” Female Luer Lock
   iii. Luer Activated Valve Cap, Bi-directional
   iv. Animal Balloon

- v. Super Glue
- vi. Thread
- vii. Nylon fabric
- viii. 3-D printed Nozzle/Lid to the actuator volume

B) Creating

- i. Cut the latex to your desired length
- ii. Cut the animal balloon approximately 2” longer than the latex
- iii. Take the nylon kite fabric and sew a tight sheathing around the latex, continue the sheathing so “un-scrunched” about 2-2.5” longer than the piece of the latex.
  1. The two ends of the sheathing (about 0.5” on both ends) will need to be looser than the rest of the sheathing to allow the sheathing to go over the nozzle tip and the female luer lock at the other end
- iv. Thread the sheathing over the latex, our best practice was to use a long thin rod
  1. Tape one end of the latex onto the rod tapering it down until you get back to the rod
  2. Slide the sheathing up the other end of the rod and over the now tapered end of the latex
- v. Scrunch the sheathing, our best practice was to
  1. Keep the latex on the rod
  2. Lightly pull on one end of the latex to stretch it (hold the end of the sheathing too)
  3. Lightly scrunch the portion of sheathing closest to where your pinching and pulling
  4. Let go of the end of the latex and it will naturally scrunch up more of the sheathing as it returns to its rest state
- vi. Attach the latex to the nozzle of the actuator, pushing the latex as far down onto the nozzle as possible
  1. Pull the sheathing down over the nozzle once the latex is secured
- vii. Thread the animal balloon through the latex and nozzle with the animal balloon sticking out about 1” on both sides
- viii. Attach the 1/4” Female Luer Lock to the open end of the animal balloon and latex
  1. Once the luer lock is pushed in
     - a. Roll the animal balloon down and apply super glue to the barb of the luer lock, then roll the balloon back on top of luer lock
- ix. Tie down the latex and sheathing onto the nozzle
- x. Tie down the animal balloon, latex and sheathing onto the leur lock
- xi. Attach the Luer Activated Valve Cap to the Female Luer Lock
- xii. Let the glue set for 24 hours

3.9.2: Wrist Joint

The final design of the wrist joint consists of six unique components joined by glue, rods, and bearings.

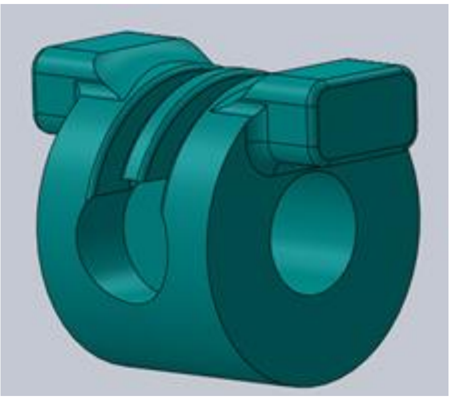

Figure 37: Wrist Joint Final Gear

The gear serves as the junction point between the wrist plate and the structure. It has ridges for the pulley strings to sit into, perpendicular holes for two attachments with rods and bearings, and two tabs for connection to the arms. The ridges result in a reduced radius where the pulley interacts with the gear, reducing the amount of less linear motion required to achieve the full range of motion. The three holes in the gear are designed so that four bearings can be inserted. The bearings are used to ensure smooth rotation with negligible friction. Locating the bearings in the gear allows for direct rod insertion into the wrist plate and structure pieces. The tabs provide multiple faces for glue between the gear and arms, and create separation between the structural components and the arms. While the gear and arms are fixed to each other, designing all three as one part would not be feasible because it would prevent access to the hole in the gear corresponding to the structure axis. Also, it would likely be very difficult to 3D print, with many opportunities for failure during the print.

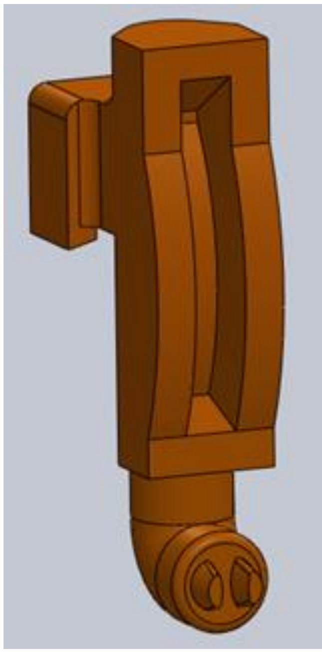

Figure 38: Wrist Joint Final Arm

The arms share the same functions, but have different dimensions and geometry to account for the different ranges of motion of radial and ulnar deviation. The main features of the arm are a tab receiver, curved slot, and tail ridge. The tab receiver fits onto the gear tab, with enough room between the gear body and arm body for the structure component. The curved slot receives an axle from the wrist plate. The use of two arms with slots prevents the wrist plate from translational motion with respect to the gear. The top and bottom edges of the slot provide hard stops to wrist plate rotation, and correspond with human radial and ulnar deviation limits.

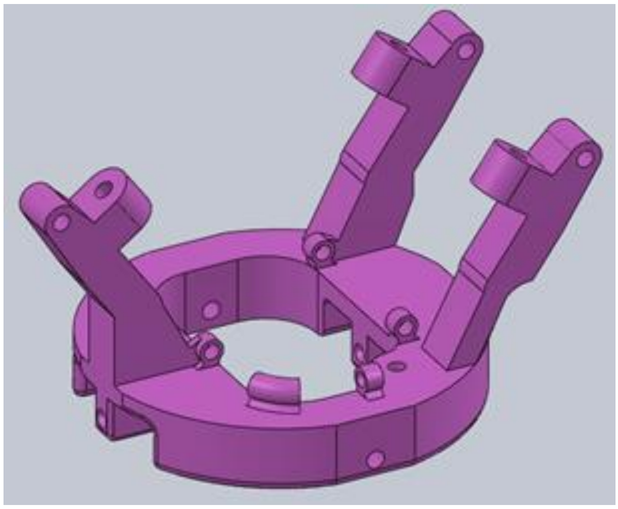

Figure 39: Wrist Joint Final Wrist Plate

The wrist plate is the base of the gripper, and the feature that reflects the movement of the wrist joint. The wrist plate is attached directly to the gear by rod and bearing, and has rotation about that axis restricted by interaction between its rods and the arms. The wrist plate has a cross-sectional area within the same range as the average human wrist, and an inner cross-sectional hole which prevents interference between itself and other components of the wrist joint. Cutouts along the bottom face of the wrist plate are necessary to ensure full flexion-extension rotation without interference with the structural components.

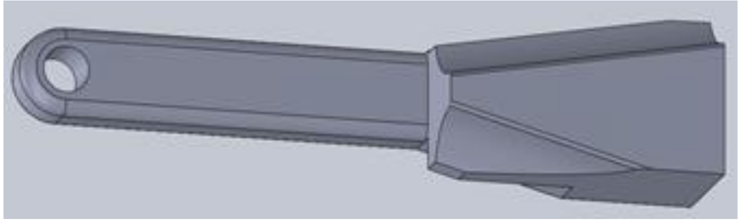

Figure 40: Wrist Joint Final Structure

The structural components are mirrored versions of each other to account for the difference in range of motion of flexion and extension. The lower geometry is a means of increasing cross-sectional area to reduce the stresses associated with horizontal positions. The lower geometry is designed so that the full range of flexion-extension motion can be achieved without interference with the wrist plate. The thickness of the upper geometry of the structural components is related to the gap between the gear and arm bodies. Connection of the wrist joint to the overall structure was planned to be achieved by extending the structural components downward to a mounting point, so that there wouldn't be interference with the Corkscrew Actuators.

3.9.3: Actuator

The final design of the Corkscrew Actuator is made up of a chamber, nozzle, coupler, threaded shaft, hollow plunger shaft, and plunger head. Figure ___ below shows a section and isometric view of the final actuator design.

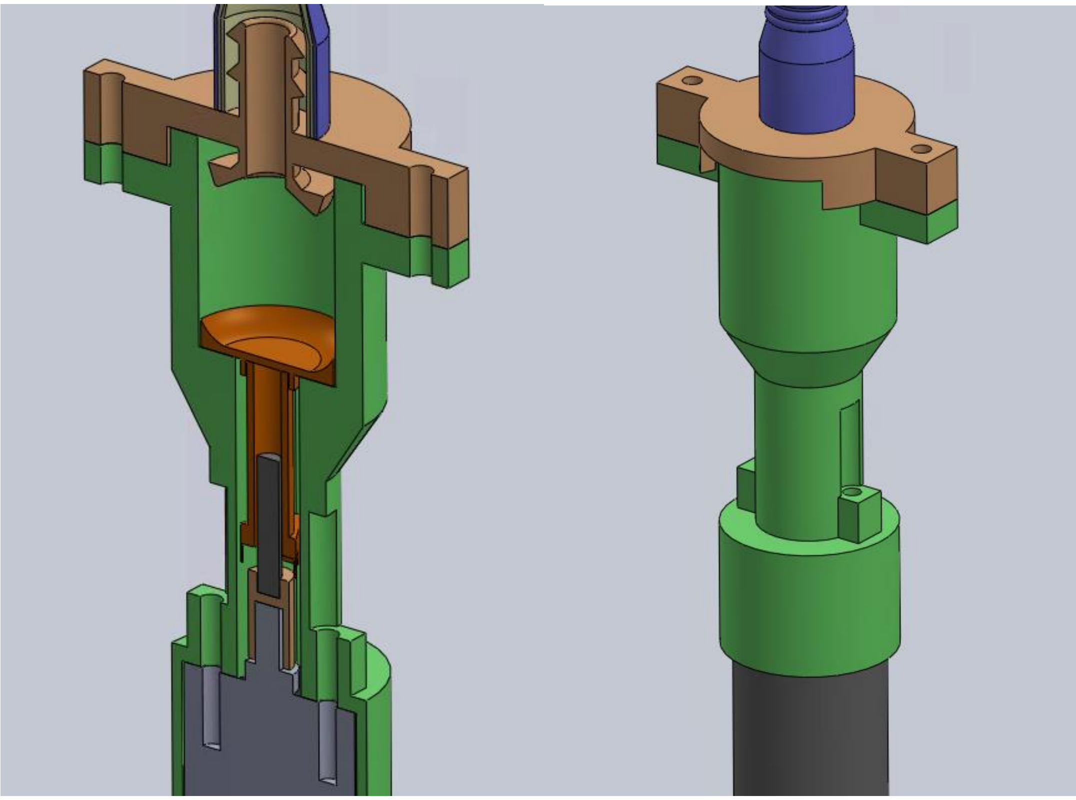

Figure 41: Final iteration of Corkscrew Actuator design

The function of the chamber remained constant since its conception, however with the second motor, holes for screw mounting were added due to the difficulties involved in securing the motor from the bottom. This also resulted in the removal of the motor support piece seen in previous iterations. Additional aspects of the final chamber include an actual chamber for the HydroMuscle reservoir, a triangular shaft to prevent nut rotation, and two mounting holes for the nozzle. The length of the chamber creates a volume of space that is larger than necessary in order to compensate for the lip geometry of the nozzle, and the fact that the bag restricts the reservoir diameter to less than that of the chamber.

The nozzle serves as the physical connection between the reservoir and the latex tube. The ridges enable a secure attachment for the latex, and the inner diameter is as large as possible for as little flow obstruction as possible. The lip provides geometry to which the bag can be secured, and contains an angle to ease the transition from the chamber diameter to the nozzle inner diameter for the fluid.

The coupler is a 3D printed part that joins the shaft of the motor to the threaded shaft. This part is necessary because a threaded shaft is necessary for the Corkscrew Actuator, but the motor shaft was not threaded.

The threaded shaft allows the interaction with the nut that is the basis of the Corkscrew Actuator concept. It is a 5-40 shaft, which means there are 40 threads per inch. This leads to more motor rotations being required to extend the HydroMuscle a specified distance, but therefore the motor torque required is decreased, as less force is needed per rotation.

The hollow plunger shaft is necessary to allow room for the threaded shaft and to house the nut. The length of the chamber space drives the length of the plunger shaft, length of the threaded shaft, and length of the chamber triangular shaft. The plunger shaft geometry that catches the nut is also the geometry that matches the chamber triangular shaft so that the nut cannot rotate.

The plunger head pushes on the HydroMuscle reservoir, forcing more fluid into the latex tube, causing HydroMuscle extension. The plunger head diameter closely matches the chamber space inner diameter, but not exactly, as a true seal is not required. This allows for less friction in movement than what is encountered in a typical syringe. The outer lip of the plunger head is an added measure against pinching the reservoir in the gap between the plunger head and the chamber space, along with the HydroMuscle bag.

3.9.4: Gripper

The final design of the gripper involves the wrist plate, and three finger subassemblies with three unique components each, all joined by rods and bearings. The fingers are identical and are made up of two joints, or bodies, and a linkage piece.

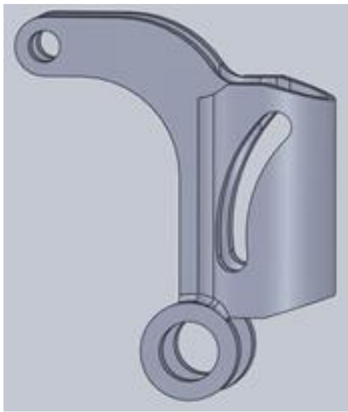

Figure 42: Gripper Final Finger Lower Body

The finger lower body is designed to undergo a smooth change in angle with respect to the wrist plate through linear actuation. A rod attached to the top of the HydroMuscle would fit into the curved slot, and as the HydroMuscle contracts, the rod would force the body to rotate. The body achieves a change in angle of approximately 30 degrees between open and closed configurations. The bottom hole is the point of connection between the finger and the wrist plate. The hole in the handle geometry is the point of connection between the lower and upper bodies.

The handle geometry is necessary to offset the upper body's axis of rotation about the lower body to achieve the desired gripping motion.

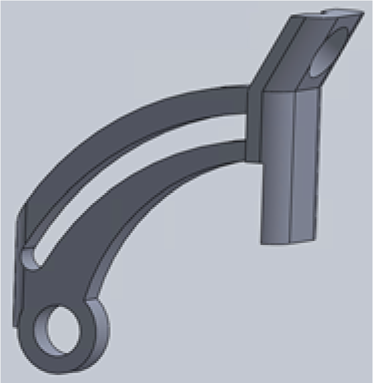

Figure 43: Gripper Final Finger Upper Body

The finger upper body is designed to undergo a smooth change in angle with respect to the finger lower body as the finger lower body rotates. The linkage piece connects from the top of the HydroMuscle to a rod reaching through the upper body curved slot, so as the HydroMuscle contracts, both the lower and upper bodies rotate about their respective axes. The body achieves a change in angle with respect to the lower body of about 30 degrees. This results in a change of angle with respect to the wrist plate of about 60 degrees. The fingertip geometry attempts to maximize contact surface area in the closed configuration without interfering with the lower body. The fingertip hole is the point where force sensor integration would occur.

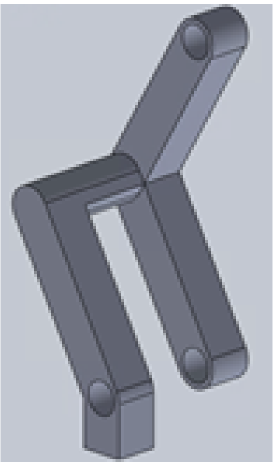

Figure 44: Gripper Final Linkage Piece

The linkage piece is designed to link HydroMuscle motion to a rod interacting with the finger upper body without interfering with the lower body. There is a small offset between the two bodies to account for the thickness of the lower body, and the angles of the piece are necessary to avoid contact with the lower body as the lower body rotates. The upper connector is angled to ensure verticality between the two rods. The lower body has square tab reception geometry (not visible) to prevent component rotation about the HydroMuscle.

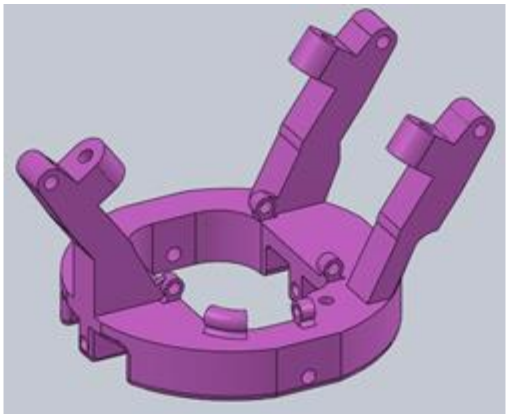

Figure 45: Gripper Final Wrist Plate

The wrist plate has three extensions to which the finger subassemblies attach. These extensions are angled to mimic the human hand in a gripping posture suitable for holding cups. The angle allows for wider finger positioning in the open configuration, and a wider grip diameter in the closed configuration. The tabs off of the extensions restrict the actuators to linear motion, and establish their offset within the finger body through their relation to the holes on the extensions. The holes on the extensions are the points of contact between the wrist plate and the finger lower bodies.

3.9.5: Controls

The code that was discussed previously is able to be run on an Arduino Nano microcontroller. For prototyping purposes, the one motor was able to run off of the 5V pin on the Arduino, but for final packaging a separate 6V battery would be installed. This is to ensure that the motors would be running at their full power. To control the DC motor controller chip, we ran two digital pins for each motor to the controller. Having the separate pins for each motor allowed for each one to be individually addressed with their own rotation commands from the script. For the force sensitive resistor, we used an analog pin to read the serial data that was being inputted. A 3.3 kΩ resistor was placed in series with the force sensor for calibration. As no calibration tests could be completed to check for accuracy, we chose a resistance in the middle range of the device to make sure it would work. The hall effect sensor required no additional calibration.

In order to achieve the fine control set by our goals, the sensors used needed to be well integrated into a feedback loop. The hall effect sensor was the main driver of the loop, as it tracked the rotational position of the motor at all times. This is seen as a number in the serial monitor window that is updated every 10th of a second. For the force sensor, it constantly tracks the resistance as it changes and calculates it into a force on the fingertip as the code runs. To achieve motion in the Corkscrew Actuator, the number of rotations needed or a very high amount to ensure closure of the gripper would be inputted into the system. If the force sensor detects that the correct amount of pressure has been obtained it stops the system, or if the force drops too fast, continues to turn the motor until it is correct.

Chapter 4: Experiment Procedures

We had two testing procedures throughout our project. There was a hand powered test and a motor powered test. They used the same setup, but the motor powered procedure has some extra steps. The supplies needed for the hand powered test are; an assembled HydroMuscle, a 3-D printed actuator cylinder and plunger, a nylon thread, a sheathing bag the size of the actuator volume, a syringe, water and a few screws and nuts.

First, take the nylon bag and tie it to the lip on the bottom of the HydroMuscle's nozzle. Insert the plunger into the actuator volume and then connect the HydroMuscle to the actuator using the screws and nuts. Draw about 10 mL of water into the syringe and attach the syringe to the luer activated cap. Plunge the water into the HydroMuscle, the system is full when the Latex becomes stiff. To ensure there is no air in the system, pump the syringe a couple times, Air should begin to accumulate above the water in the syringe as you continually pump the syringe. While pressing down on the plunger of the syringe, twist it off of the luer activated cap to ensure no air gets into the system. To see extension of the HydroMuscle, use a thin rod of some kind to push on the bottom of the plunger.

The motor powered test needed a 5-40 thread shaft and nut, a 3-D printed brace to hold the motor in place, and a coupler to connect the 5-40 shaft to the d-profile shaft on the end of the motor. The procedural steps are very similar as well. The only changes you need to make to the above steps is to glue the 5-40 threaded nut onto the bottom of the plunger before inserting it into the actuator and to wait to fill the system with water until after the motor is attached.

Once you have the HydroMuscle connected to the actuator, take the motor and glue the coupler to the d-profile shaft and glue in a 5-40 threaded shaft. It is imperative that the coupler and shaft are sitting perfectly straight on the motor or the system will be thrown off, remember the glue needs to be set for 24 hours to reach its maximum strength. Once the glue is set, screw the motor into the bottom of the plunger. Then use the motor brace, screws and nuts to secure the motor to the rest of the system. The next step is to attach the electrical components and use the code to bottom out the plunger in the actuator. Once the plunger is bottomed out, add water into the system the same way as before, ensuring to pump the syringe to get the air bubbles out of the system. Once the system is full, you can run the full code to actuate the HydroMuscle.

Chapter 5: Experiment Results

Our experimental test results drove the design process for our HydroMuscles and Corkscrew Actuator. For our first experiment, we used a Greartisan DC 12V 600RPM N20 High Torque Speed Reduction Motor, 1/8” thick latex, a finger cot as our water reservoir, and the first 3D printed iteration of the Corkscrew Actuator. After testing, we had minimal actuation of the HydroMuscle. We noticed leaking in the actuator, and the motor was not supported from behind. This caused the motor to unscrew itself, rather than push our plunger. To prevent this from happening, we designed a motor brace to keep the motor in place.

Experiment two was set up very similarly to experiment one. We slightly increased the width of the nozzle on the actuator to allow for more water flow. After testing, we had no leaking, but once again no actuation. This was when we figured out we needed to significantly increase the amount of water in the system. We also realized that the current design of the actuator cap left us with a lot of extra space inside the reservoir chamber. The water pushed by the plunger would move into that extra space, rather than the HydroMuscle. This led us to make design changes to the cap of the Corkscrew Actuator. Furthermore, we decided as a group that we needed to successfully see actuation from a HydroMuscle before we worry about incorporating the motor.

Experiment three is where we began to run into sealing issues. Once we increased the amount of water in the system, the pressure was much higher inside the system. For experiment three, we wanted to test for leaks by connecting the HydroMuscle directly to a syringe. Immediately, we noticed much more resistance when we pushed on the syringe. After testing, the plug that we had hot glued to the top of our HydroMuscle shot off as soon as we started to get some actuation of the HydroMuscle. We learned that the current plug system would not work for our specific application, and we needed a new solution.

For experiment four we switched from 1/8” thick latex to 1/16” thick latex. We hypothesized that this would allow us to see more actuation out of the HydroMuscle. We were still waiting on new caps to come in, so unfortunately we did not have a new cap system for this test. We assembled the actuator and HydroMuscle system together, and manually pushed on the plunger to see what actuation we would get. Additionally, we decided to increase the volume of liquid even more. Furthermore, we decided we needed to design a way to protect the reservoir from being pinched between the plunger and inner wall of the Corkscrew Actuator.

Experiment 5 was a successful day of experimenting for us. A new 3-way valve came in that we could use as the cap for our HydroMuscle. This new valve allowed for a much more efficient and effective way for us to fill our system with water, and bleed it of air. The new cap in combination with the thin walled latex allowed us to see our first significant actuation of the HydroMuscle when we applied a significant force by manually pushing on the plunger. Also, this was the first test we incorporated a protective bag (made of the nylon kite fabric) around the latex water reservoir. Even when we were applying a large force with the plunger, we ran into no issues pinching the bag. After successfully extending the HydroMuscle by hand, we decided to finally test the Corkscrew Actuator with our motor. Quickly, we realized that it was not close to providing us with the speed or power our project required. The motor stalled out before we got any actuation out of the HydroMuscle. We knew we needed to lower the force required to expand the HydroMuscle.

For experiment 6, we needed to lower the force required to expand the HydroMuscle. We experimented with this by designing two volume shapes for our Corkscrew Actuator. One design was the original short, wide volume and another with a long, skinny volume. After connecting the hydrouscle to each of the new Corkscrew Actuator designs, we found it was much easier to manually actuate the long, skinny volume. Unfortunately the latex finger cot that we had been using for the entirety of the project burst during testing, leaving us back at square one with sealing issues again.

Experiment 7 was when we finally were able to successfully bring all of the aspects of our project together. We had received new luer lock caps, which were even better than the 3-way valves we had previously been using. We were set on using the long, skinny design for our Corkscrew Actuator to lower the amount of force required to actuate the HydroMuscle. We switched from the latex finger cot as our water reservoir, to an animal balloon that ran throughout the entirety of the latex. This helped us waterproof our HydroMuscle, as there was only one waterproof seal required at this point. When we brought all of these elements together, we were able to successfully actuate the HydroMuscle with a significantly lower force than before. Unfortunately, we were not able to test this with the newer DFROBOT FIT0521 motor. We were working on finding a way to secure it to our Corkscrew Actuator body before the COVID-19 pandemic struck, halting our progress.

Chapter 6: Final Status

6.1: HydroMuscle

The final design of the system would require five HydroMuscles. Two HydroMuscles would be used for the two degrees of freedom of the wrist, and the other three would be located within the lower body of the gripper finger, as discussed in the Gripper section. The HydroMuscles in the fingers would either be slightly scaled down from the final HydroMuscle design, or the gripper finger lower body hole would be widened to accommodate the HydroMuscles, depending on the capabilities of the latex tubing. The two wrist HydroMuscles would be exactly as designed, but the finger HydroMuscles would require transport tubing from the Corkscrew Actuator and reservoir to the HydroMuscles. One Corkscrew Actuator would be used for all three finger HydroMuscles, so a splitter would be used to split the fluid line from the Corkscrew Actuator to each of the three HydroMuscles. In order to achieve this, a Luer cap would be integrated with the nozzle on the reservoir, allowing for transport pipe connection. The finger HydroMuscles would be equipped with Luer caps on both ends, for easy filling and bleeding, and for easy connection to the transport tubing. The gripper linkage piece would be fixed to the top Luer caps of the finger HydroMuscles. The two wrist HydroMuscles would be attached to the wrist by pulley systems, tied off on the Luer caps. Both the wrist and finger HydroMuscles will require an antagonistic elastic element. Springs were planned to be used with the wrist degrees of freedom, and elastic elements along the backside of the fingers were planned to be used to return the fingers to the open extension configuration.

6.2: Wrist and Gripper

The wrist joint and gripper were developed to a point of satisfactory sizes and ranges of motion. While a structure was not finalized, the plan was to extend the existing structure downward without increasing cross-sectional area in order to avoid interference with flexion-extension motion. The edge of the wrist plate was to be linked to the structural body by a sheathing of the same material as used in the HydroMuscles. This would prevent access to the internal components of the device while not interfering with the wrist joint range of motion.

Additionally, finalizing actuation was not accomplished due to social distancing protocol, but only would have been a matter of integrating the wrist and gripper design with Corkscrew Actuators. The degrees of freedom of the wrist joint and gripper were designed to be actuated by linear motion. Flexion-extension, the rotation of the small center gear of the wrist joint about the support axis, was planned to be controlled by two pulleys linking the gear’s rotation to a HydroMuscle and a counter spring. Wrist deviation was also designed to be controlled by a HydroMuscle and counter spring through a pulley system, with the arm ridges maintaining the pulley’s direction of actuation on the wrist plate at any flexion-extension position. The fingers were designed to allow for flexion, or gripping, to be driven by a HydroMuscle, with an antagonistic elastic element used to return the finger to its open configuration. Each of the three fingers were planned to have a HydroMuscle reaching from a fixed point on the wrist plate into the lower finger joint, and each of these three HydroMuscles were to be linked by flexible piping to one Corkscrew Actuator located below the wrist joint. Using one Corkscrew Actuator for all three Gripper HydroMuscles restricts the gripper to only one active degree of freedom, but the use of HydroMuscles creates compliance in this movement. The grip strength exerted on an object is naturally limited, as the normal force exerted on the finger by the object will be greater than the tensile force of the latex in the HydroMuscle. The fingers were also designed for force sensor integration. A force sensor on at least one fingertip would be flush with the finger so that grip force can be measured. Wiring from the force sensor would run down the back side of the finger and be threaded through the wrist plate, similar to the fluid lines to the finger HydroMuscles.

6.3: Actuator

The Corkscrew Actuator itself is finished with a working proof of concept, however due to the COVID-19 pandemic we were unable to integrate the actuators into a final prosthetic package. We anticipated having three separate Corkscrew Actuators contained in a self packaged system; one for each degree of freedom at the wrist, and one to control all three of the gripper HydroMuscles. The wrist HydroMuscles would be attached directly to the Corkscrew Actuator using the balloon animal reservoir mentioned in the previous sections. To keep the extension and contraction of the wrist HydroMuscles completely linear, we planned to attach the end of the muscles to small rails via a 3D printed part connected to the Luer cap and slide along the rails. As mentioned earlier, the HydroMuscles themselves would not be attached directly to the wrist joint, and would instead be connected with pulleys fixed to specific points on the wrist joint. The Corkscrew Actuator/HydroMuscle subassemblies would each be positioned on one side of each direction of rotation, and would be opposed by springs working in opposition to the elasticity of the latex HydroMuscles. The third and final Corkscrew Actuator in the prosthetic would serve to control all three gripper HydroMuscles at once. For this actuator, we anticipated using standard Luer tubing to connect with the HydroMuscles located on the gripper. Ideally, a 3 way Luer splitter would be attached directly to the nozzle and balloon animal reservoir on the Corkscrew

Actuator, and three lengths of Luer tubing would run from the actuator’s location in the forearm area up through the wrist plate into the base of each of the gripper HydroMuscles.

6.4: Electronics

Had this project been fully completed we would have had to reorganize much of the electrical system. With two more DC motors being used, an external power supply would be needed to ensure proper voltage is being delivered. One of the largest challenges with this when doing research at the beginning of the project, was once again sizing. Most rechargeable battery packs with a decent size were too large to try and fit in the size of a human wrist. One idea that we had but never pursued, was to use coin batteries as they are much smaller and can still hold a respectable charge. To help with spacing issues and organization of the wires, we had also planned on creating a custom Printed Circuit Board using software like Eagle. This had to be cut out from our project as there would have not been enough time to wait for the shipping delays. We had already run into these issues trying to get a new motor and didn’t want to potentially postpone further testing of our system. Where the project stands now though, is a good proof of concept to show that the control system works on what we were able to build. There are multiple sensors being used to track the position of the motor as well as the grip strength being felt.

6.5: Code

The code that we were able to build ended up being quite successful for the assembled system. Although it was not able to go through as much testing as it should have due to time constraints, we were able to achieve the control of the motors using a force feedback loop. The hall effect sensor on the motor and the force sensor on the fingertip were used in tandem to start and stop the motor as needed. Unfortunately due to our time being cut much of the calibration for the system was not able to be completed. There is a good chance that both the PID system and the force sensor are not completely accurate as they were instantiated with only the basic information. Had the system been completely assembled we would have been able to test what values worked better than others and adjusted the system accordingly. There are also some bugs left in the system that have not been quashed, but would likely have been easy to fix if we were able to have more time to finish the project. Overall, everything works as planned, but could have been more polished had the global pandemic not occured.

6.6: Conceptual Final Product

The final package, although physical developments could not be made, was conceptualized to be a simple cylinder with mounting points for the various components of the design. It would consist of a battery pack toward the bottom away from the wrist joint, a means of securing the three Corkscrew Actuators, and a connection point for the wrist joint structure. The outer edge of the wrist plate would be connected to the structure cylinder by the same fabric used for the HydroMuscle sheathing, in order to provide coverage without interfering with motion capabilities. The fluid transport piping for the finger HydroMuscles would run through the center opening in the wrist plate, as would the electric wiring for the finger force sensors. The circuitry would ideally be printed onto a small PCB, and placed toward the bottom of the Corkscrew Actuators, near the battery pack. If necessary, a light metal such as copper would be implemented between the battery pack and PCB to transport heat away and out of the system.

Assembly would likely be done in stages. The wrist and Gripper subassembly could be pre-assembled. Next, the wrist Corkscrew Actuator and HydroMuscle subassemblies would be attached to the wrist via the pulley systems, then mounted into the structure. The finger

HydroMuscles would be installed in the fingers during the wrist and Gripper subassembly development, and the finger Corkscrew Actuator could be mounted and the transport piping attached separately. Once all three Corkscrew Actuators are mounted in the structure and attached to the wrist and gripper subassembly, the wrist structural component can be secured to the overall structure. From here, assembly would continue at the other end of the structure cylinder, as the wiring from the Corkscrew Actuators and force sensors would be installed onto the circuit board. The circuit board would be mounted and attached to the power source. Then the battery pack would be attached at the bottom, closing the system, like a cap on a bottle.

Chapter 7: Future Work

Potential areas of future work using information and design from this project include prosthetics, assistive devices, robotics, and more. Even though the final state of the project is segmented, each segment has its own features to take advantage of. This includes novel uses of the Corkscrew Actuator to achieve compliant motion, continued design on the wrist and gripper to achieve more degrees of freedom, and the implementation of additional sensors in situations requiring high accuracy.

The Corkscrew Actuator is a compact means of achieving compliant motion. Its scalability requires adjustments to the motor and the thickness of the latex tube, but the overall housing can easily be sized up to meet requirements. Also, steps to assembly will remain consistent. The use of the balloon animal leads to only one seal, which is a critical point in the design, especially when adjusted for greater force output and higher pressure. It is desirable to utilize the Corkscrew Actuator and HydroMuscle instead of rigid components in order to inherently mimic the compliance seen in human muscle. The HydroMuscle is favorable to the use of a rigid element and elastic element in series because its position is dependent on the amount of fluid in the system, which is dependent on the position of the motor, whereas an elastic element in series will have variable stretch depending on the amount of force placed on it. Also, valves could be implemented to allow for the actuation of multiple HydroMuscles from one actuator, while the use of an elastic element would require a motor for every degree of freedom. The Corkscrew Actuator allows for more portable HydroMuscle applications, and is lightweight due to the use of plastic in the housing. The main source of weight is the motor. The use of plastic also leads to a cost efficient design aside from the motor. The main tradeoff in future applications of the Corkscrew Actuator and HydroMuscle will be the proportionality between strength and required motor size and cost.

The HydroMuscle is appealing in robotics applications that require a soft grip. In this project, the use of the HydroMuscle to contract the finger means the finger grip strength is limited by the tensile strength of the latex tube. This means the HydroMuscle will naturally have a limited strength grip even if the motor continues rotating, as the normal force of the gripped object on the finger will quickly overcome the tensile strength of the latex once contact is made. Rigid grippers entirely rely on sensor feedback to moderate grip strength. This could be useful in situations requiring robot-human interaction, to prevent injury from limbs caught in the grip.

In order to further develop this project into a commercial prosthetic, a method of control would be required. Electromyography is a popular method of control for wrist and hand prosthetics, and uses signals from the remaining muscles in the remaining forearm to activate motion. While wrist flexion and deviation is desirable for amputees, the overlap in muscle responsibility makes it difficult to determine patient intent between wrist flexion and finger grip, as noted in the background. Modifications to the gripper to increase the number of degrees of freedom may also be necessary in order to provide multiple grip options. The use of both Corkscrew Actuators and rigid actuation may be beneficial in volume conservation, as compliant motion may not be necessary in every active degree of freedom.

If our group had significantly more time and budget to develop this project, areas of improvement would include the motors and sensors used, a method of control, and additional degrees of freedom. A larger budget would allow for stronger motors at a similar size, allowing for stronger HydroMuscles. The addition of a means of actuating pronation-supination motion or the implementation of the design with a device that provides such motion would increase the device usability for amputees. Additional degrees of freedom within the gripper could allow for an increased number of usable grips, although it would complicate control. Switches or toggles could be paired with electromyography to achieve the desired level of control.

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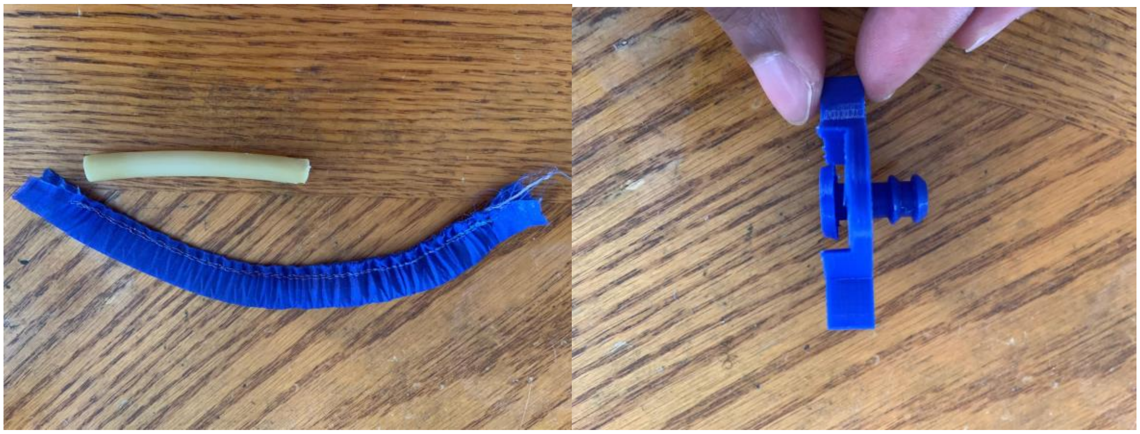
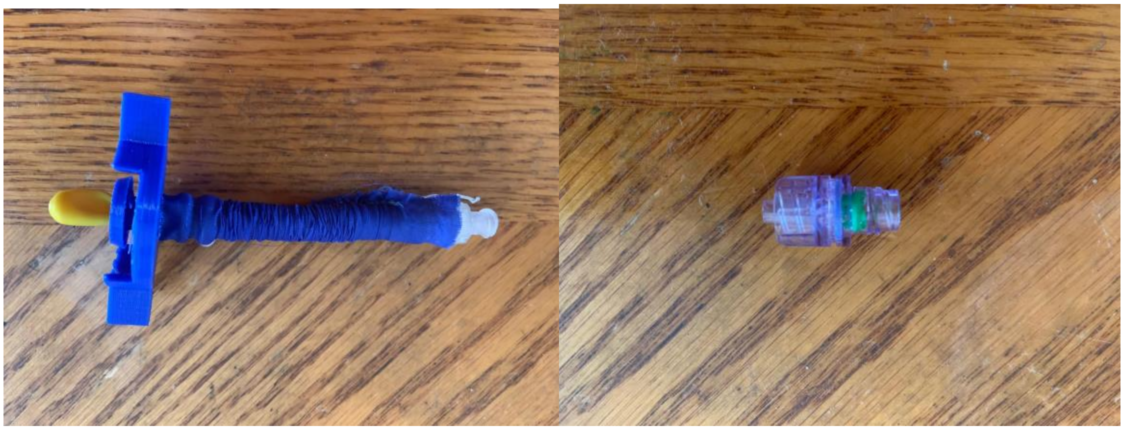
Appendix A - HydroMuscle Assembly Pictures





Appendix B - Arduino Code

```
#include <PIDController.h>
volatile long int encoder_pos = 0;
PIDController pos_pid;
int motor_value = 255;
unsigned int integerValue=0;  // Max value is 65535
char incomingByte;

//Pressure Sensor Constants Setup
const int FSR_PIN = A7; // Pin connected to FSR/resistor divider

// Measure the voltage at 5V and resistance of your 3.3k resistor, and enter
// their value's below:
const float VCC = 4.98; // Measured voltage of Ardunio 5V line
const float R_DIV = 3003.0; // Measured resistance of 3.3k resistor

int isGrip = 0;
int homePOS = 0;

void setup() {
  Serial.begin(9600);
  pinMode(2, INPUT);
```

```
  pinMode(3, INPUT);
  pinMode(9, OUTPUT);
  pinMode(10, OUTPUT);
  attachInterrupt(digitalPinToInterrupt(2), encoder, RISING);

  pinMode(FSR_PIN, INPUT); //Pressure Sensor Pin Setup

  pos_pid.begin();
  pos_pid.tune(15, 0, 1500);
  pos_pid.limit(-255, 255);
}
void loop() {

if (Serial.available() > 0) {
    integerValue = 0;
    while(1) {
      incomingByte = Serial.read();
      if (incomingByte == '\n') break;
      if (incomingByte == -1) continue;
      integerValue *= 10;
      integerValue = ((incomingByte - 48) + integerValue);
      pos_pid.setpoint(integerValue);
    }
```

```
}
   motor_value = pos_pid.compute(encoder_pos);
   Pressure_Detect();


if (integerValue == 0){
  MotorCounterClockwise(homePOS);
}
if (isGrip == 1)
{
  MotorClockwise(0);
}
else if(motor_value > 0 && isGrip == 0){
  MotorClockwise(motor_value);


}
else if(isGrip == 2){
  MotorCounterClockwise(abs(motor_value));
}
  Serial.println(encoder_pos);
  delay(100);
}
void encoder(){
```

```
  if(digitalRead(3) == HIGH){
    encoder_pos++;
  }else{
    encoder_pos--;
  }
}

void MotorCounterClockwise(int power){
  if(power > 100){
  analogWrite(9, power);
  digitalWrite(10, LOW);
  }else{
    digitalWrite(9, LOW);
    digitalWrite(10, LOW);
  }
}

void MotorClockwise(int power){
  if(power > 100){
  analogWrite(10, power);
  digitalWrite(9, LOW);
  }else{
    digitalWrite(9, LOW);
```

```
    digitalWrite(10, LOW);
  }
}

int Pressure_Detect(){

  int fsrADC = analogRead(FSR_PIN);

  if (fsrADC != 0) // If the analog reading is non-zero
  {
    // Use ADC reading to calculate voltage:
    float fsrV = fsrADC * VCC / 1023.0;
    // Use voltage and static resistor value to
    // calculate FSR resistance:
    float fsrR = R_DIV * (VCC / fsrV - 1.0);
    Serial.println("Resistance: " + String(fsrR) + " ohms");
    // Guesstimate force based on slopes in figure 3 of
    // FSR datasheet:
    float force;
    float fsrG = 1.0 / fsrR; // Calculate conductance
    // Break parabolic curve down into two linear slopes:
    if (fsrR <= 600)
      force = (fsrG - 0.00075) / 0.00000032639;
```

```
    else
      force =  fsrG / 0.000000642857;
    Serial.println("Force: " + String(force) + " g");
    Serial.println();
    delay(100);



    if(force >= 100 && force <200){
      isGrip = 1;
    }
    else if (force >200){
      isGrip = 2;
    }
    else if(force <100){
      isGrip = 0;
    }
  else //No Pressure Detected
  {
    isGrip = 0;
  }
  }
  return isGrip;
}
```